

Supernova Remnants

Nucleosynthesis &

Particle Acceleration

Jacco Vink

Astronomical Institute, Utrecht University



Contents


1. Supernova & Supernova Remnant Types
2. Collisionless Shocks & Supernova Remnant Evolution
3. Thermal X-ray Emission from Supernova Remnants
4. An Application of what we have learned
5. Non-equilibration of Temperatures
6. Cosmic Ray Acceleration by SNR shocks
7. Nucleosynthesis products observed in X-rays
8. Nucleosynthesis products observed in γ -rays



The importance of supernovae & their remnants

- SNe important as source of chemical enrichment: almost all elements $Z > 8$ come from supernovae
- SNe/SNRs provide energy (heating/turbulence) to the ISM, important for star formation
- SNRs considered to be the most important source of cosmic rays up to energies of $\sim 10^{15} \text{eV}$
- Type Ia are used as cosmological “standard candles”: their remnants may provide useful insights into their nature
- The explosion mechanism of core collapse SNe is poorly understood: SNRs may provide new insights
- SNR shocks are sites of interesting physics: collisionless shock heating, particle acceleration





Chapter 1

Supernova & Supernova Remnant Types



SN1987A

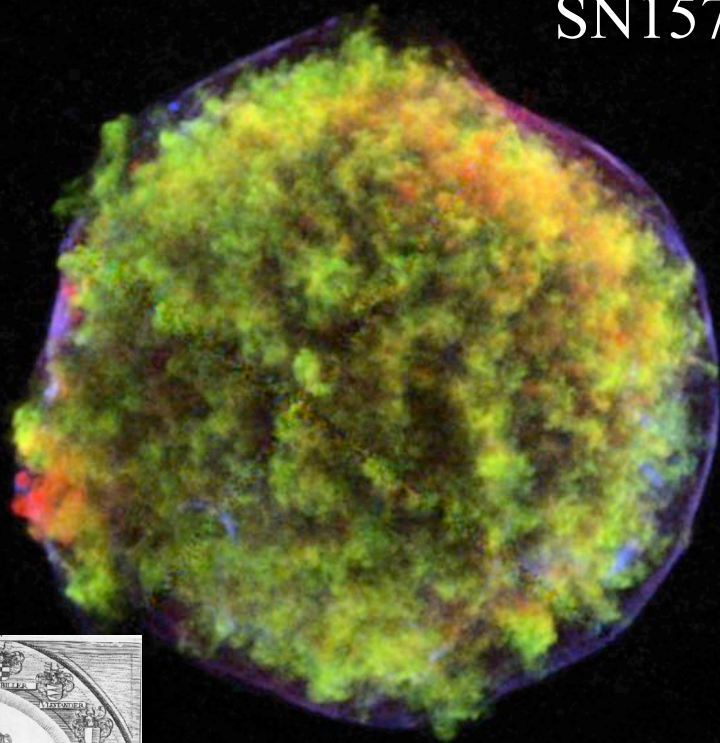


(23 Februari 1987)



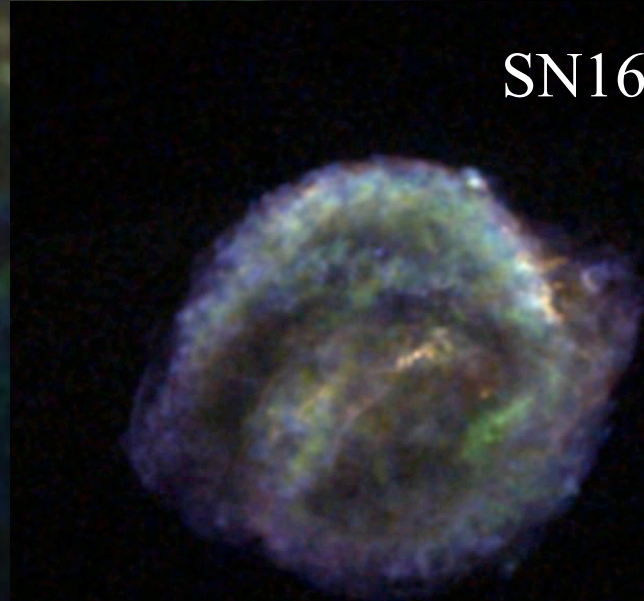
Two Historical SNRs

SN1572



Chandra

SN1604



Tycho Brahe



Johannes Kepler



SN1006



Size: 30'

The size of the full Moon

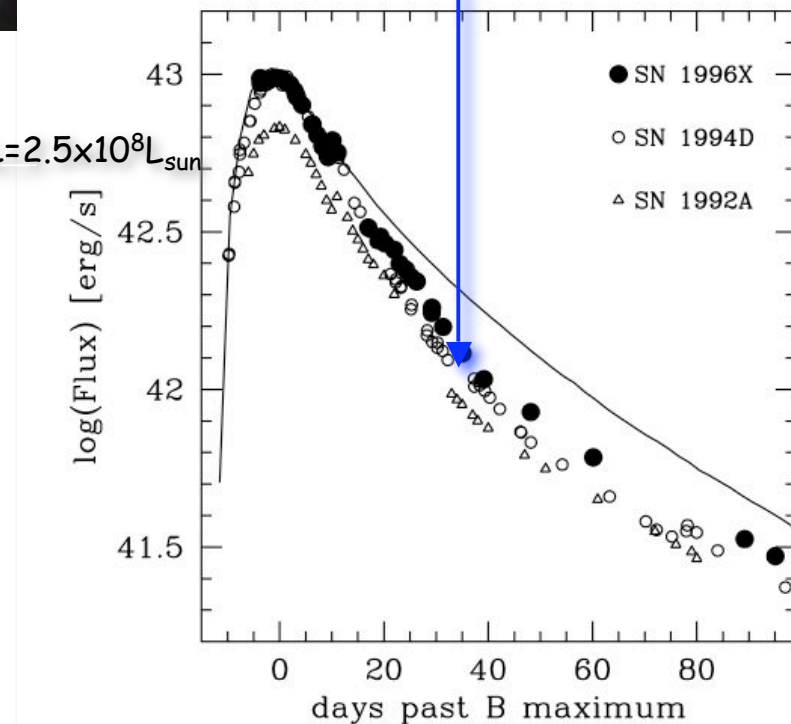
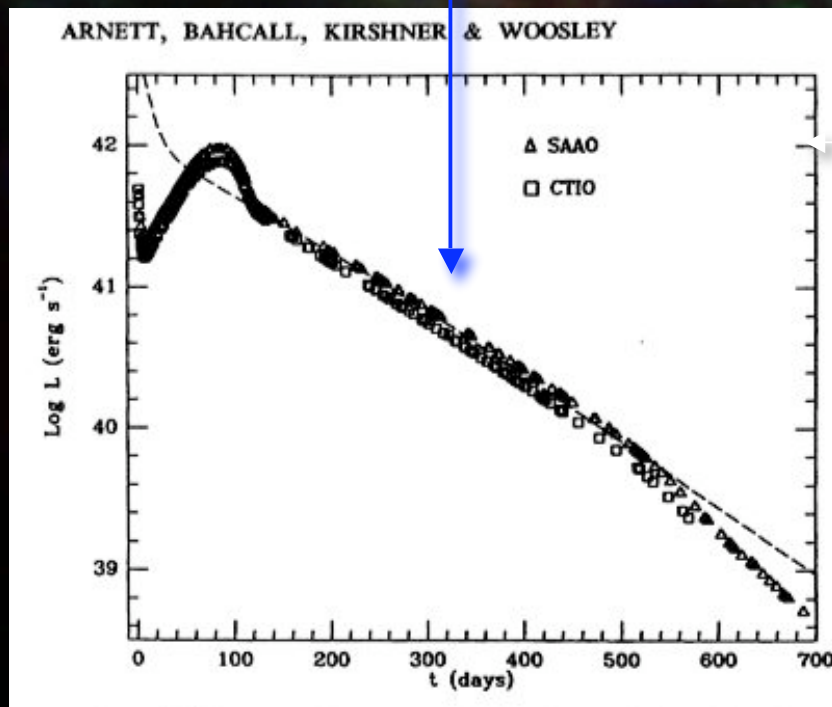
Historical brightness

-6 mag, perhaps -9 mag



Supernova light curves

Tail of light curve caused by heating by nuclear decay
(especially $^{56}\text{Ni}(8.8\text{d}) \rightarrow ^{56}\text{Co}(111\text{d}) \rightarrow ^{56}\text{Fe}$)



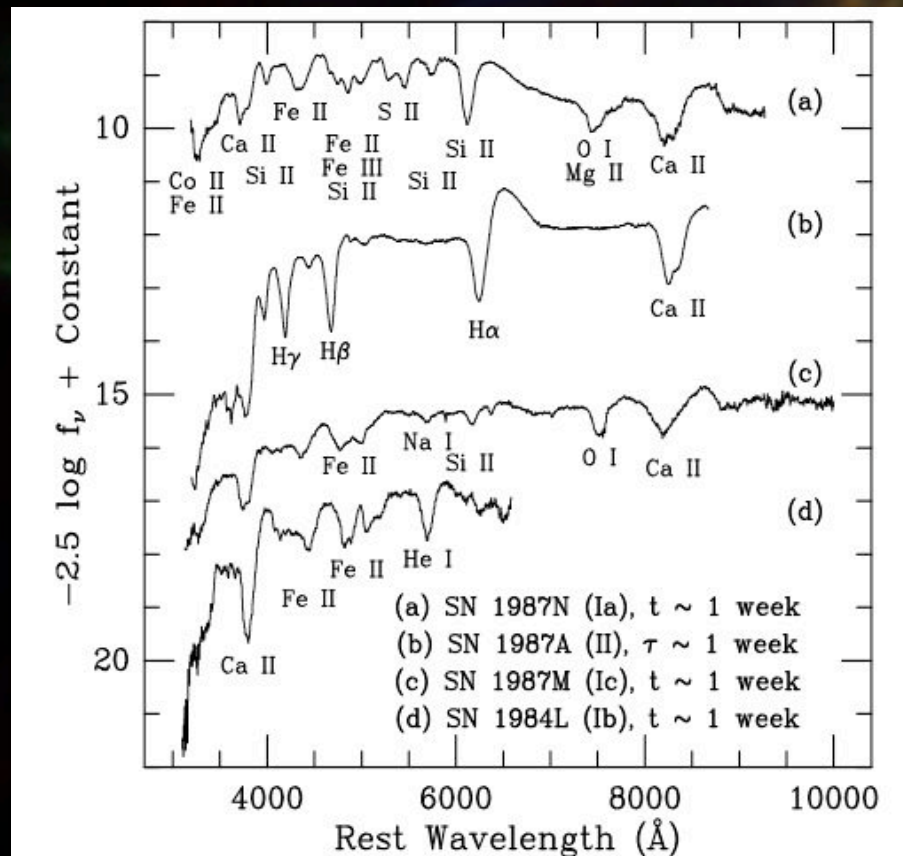
SN1987A

(a “weak” SN)

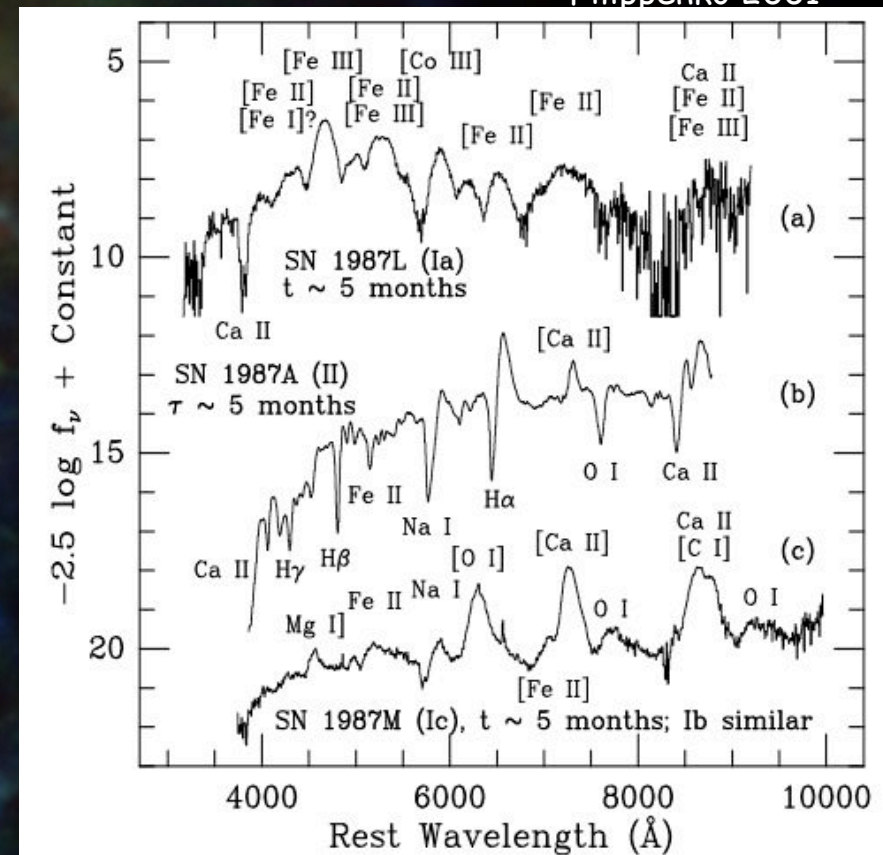
SN1992A, SN1994D, SN1996X



Filippenko 2001



After 1 week

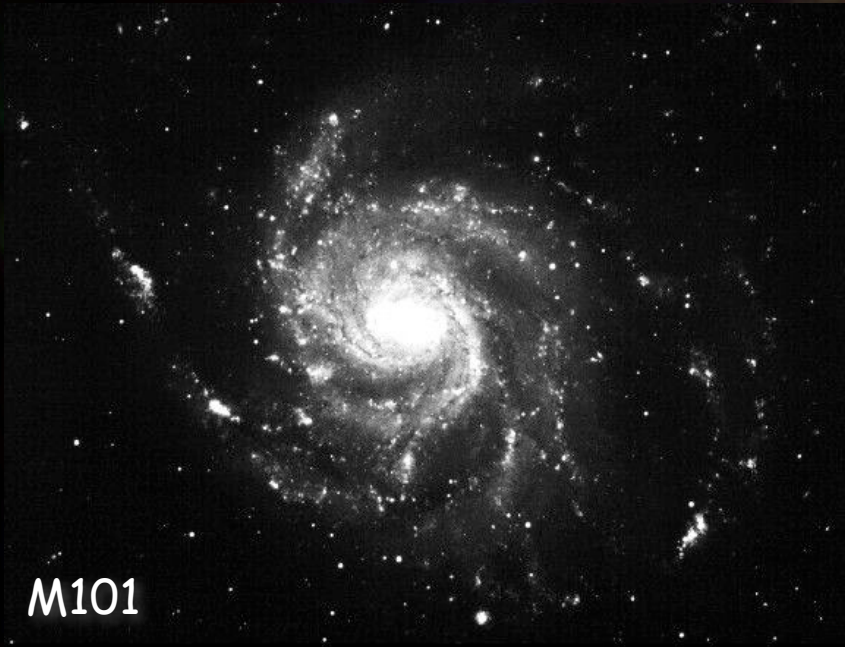


After 5 months

There are different types of supernovae
Only Type II have hydrogen

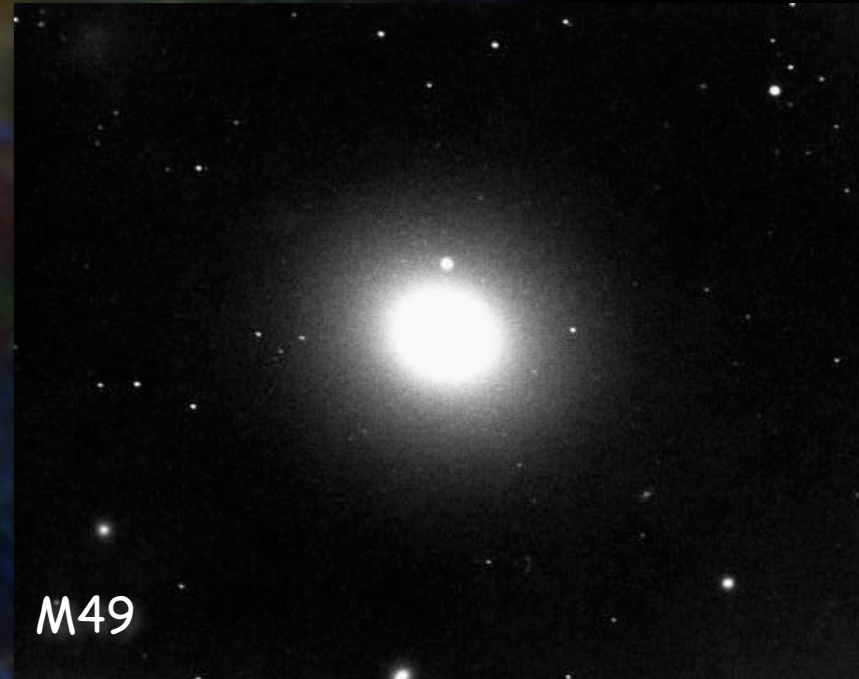


Supernova types and host galaxies



M101

Spiral galaxies:
Host all types of SNe
Stellar population:
a mix of old and young



M49

Elliptical galaxies:
Only Type Ia
Stellar population: old

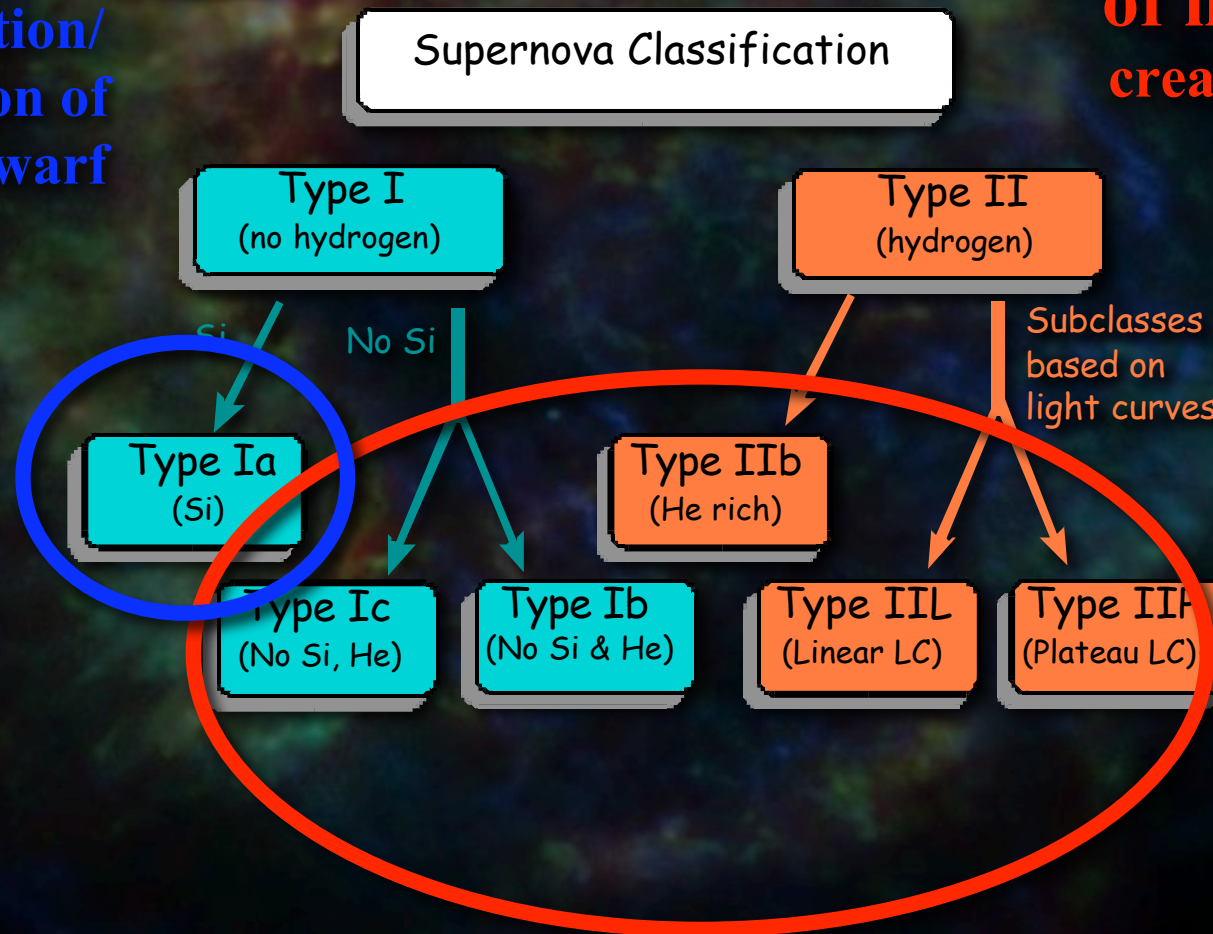
The Galaxy: ± 2 supernovae per century



Supernova classification

*Thermonuclear
explosion
deflagration/
detonation of
White Dwarf*

Core collapse
of massive star
creation of NS/BH

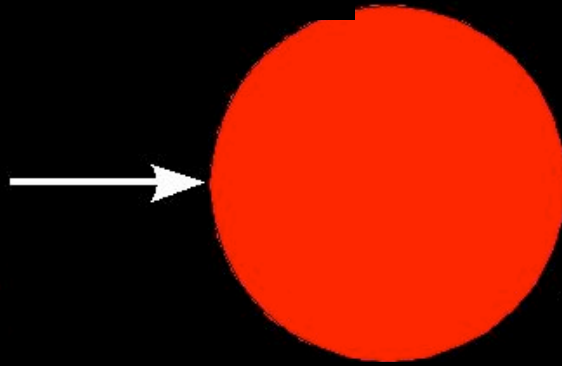


Which stars do become supernovae?

Massive stars $> 7 M_{\text{sun}}$



Main Seq.



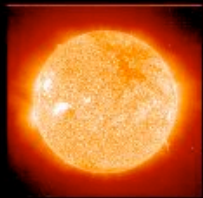
Red Super Giant Phase

Very Massive stars $> 22 M_{\text{sun}}$
Wolf-Rayet Stars



Supernova!

Stars $< 7 M_{\text{sun}}$



Red giant



Planetary Nebulae



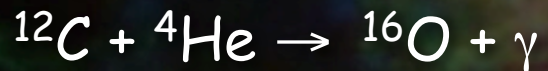
White dwarf



Nuclear fusion processes

(occurring during stellar evolution and explosion)

Helium burning ($T = 0.2 \times 10^9 \text{ K}$)



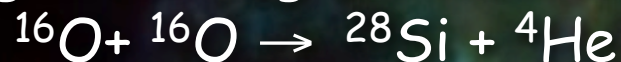
Carbon burning ($T = 2 \times 10^9 \text{ K}$)



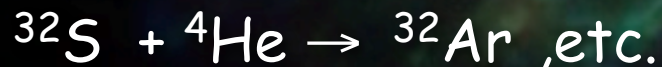
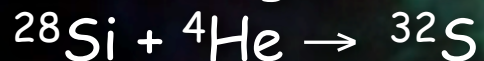
Neon burning ($T = 2 \times 10^9 \text{ K}$)



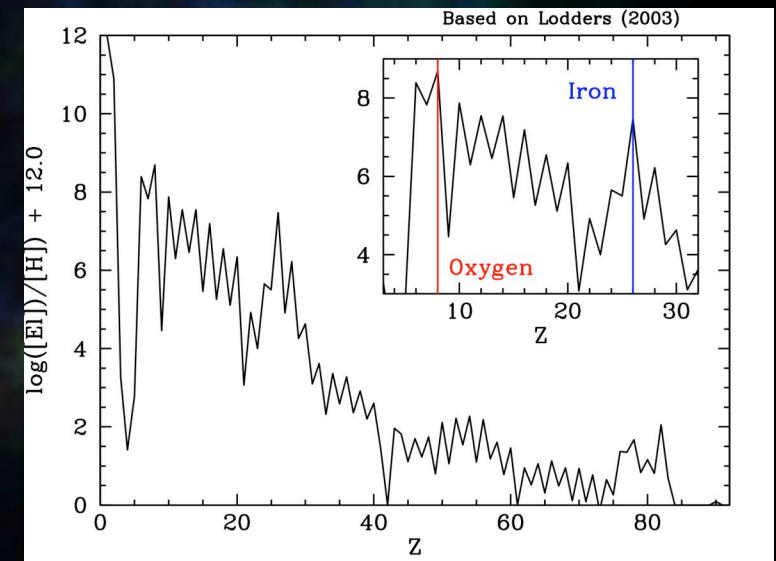
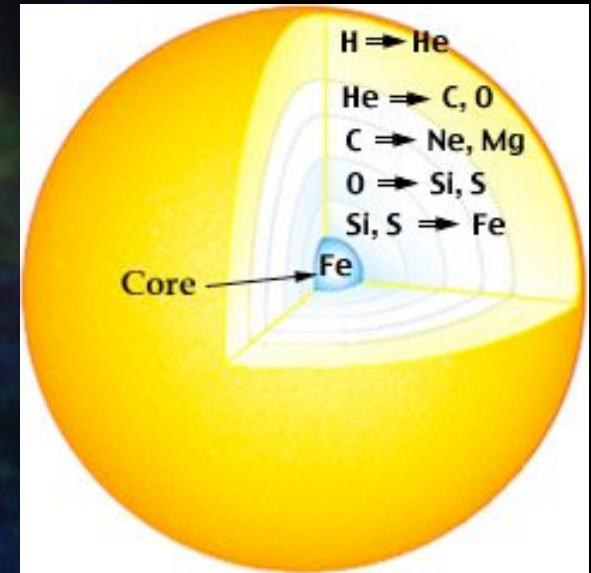
Oxygen burning ($T = 3.6 \times 10^9 \text{ K}$)



Silicon burning ($T = 5 \times 10^9 \text{ K}$)



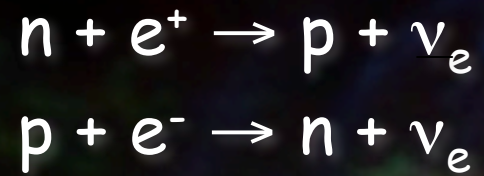
Most important product ${}^{56}\text{Ni}$
(radio-active: ${}^{56}\text{Ni} + e^- \rightarrow {}^{56}\text{Fe}$)



Solar abundance pattern



Neutrino detection



Kamiokande detected
12 neutrinos on Feb. 23 1987
from SN1987A:
Confirmation of the neutron
star creation theory!

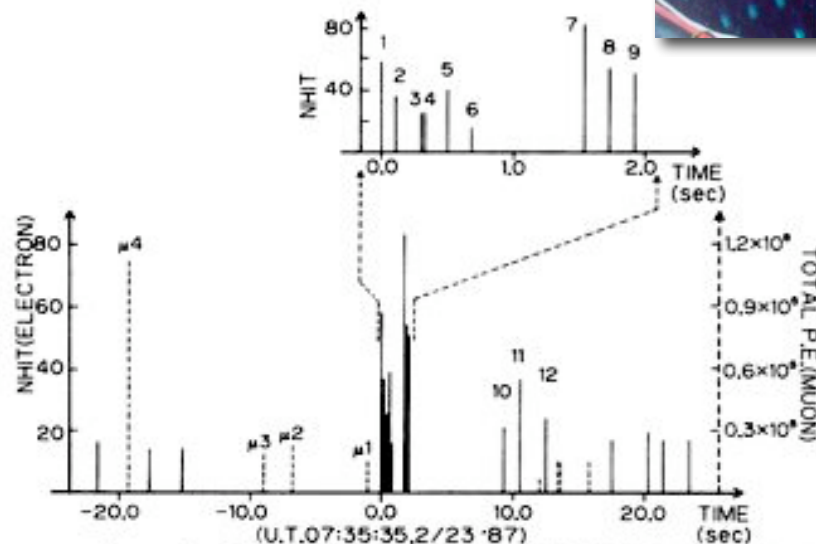
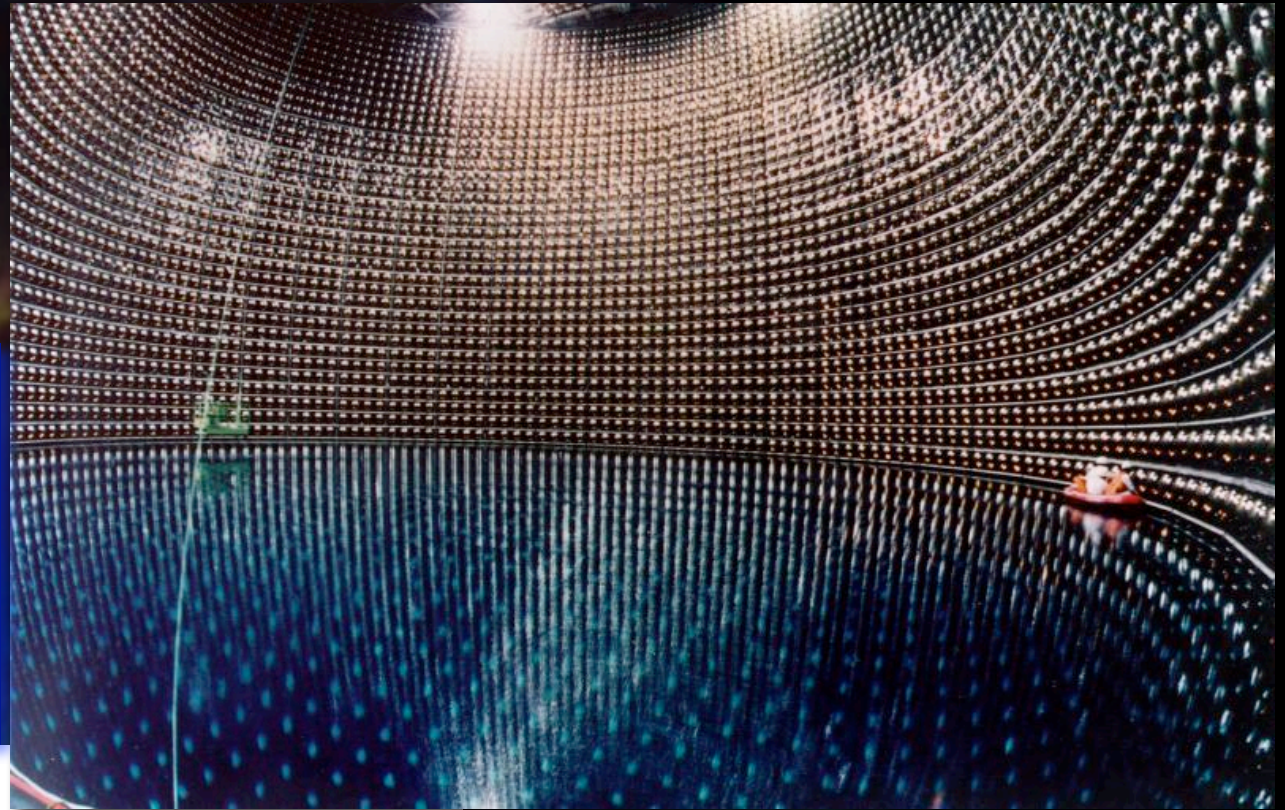


FIG. 2. The time sequence of events in a 45-sec interval centered on 07:35:35 UT, 23 February 1987. The vertical height of each line represents the relative energy of the event. Solid lines represent low-energy electron events in units of the number of hit PMT's.

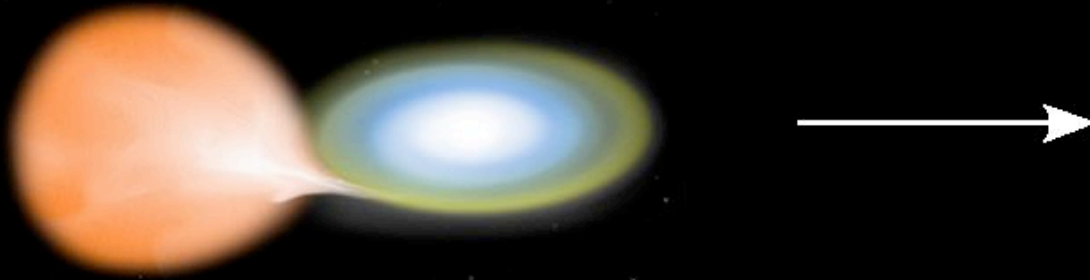
Kamiokande

Standard hypothesis for Type Ia SNe

Accreting C/O
white dwarf

Steady mass
accumulation
(need to avoid
nova explosions)

Explodes when a critical
density is reached
(near $1.4 M_{\odot}$)



Dominant nucleosynthesis product
 ^{56}Ni (radio-active)
 $\sim 0.7 M_{\odot}$



Two types of supernovae: very different sources of energy

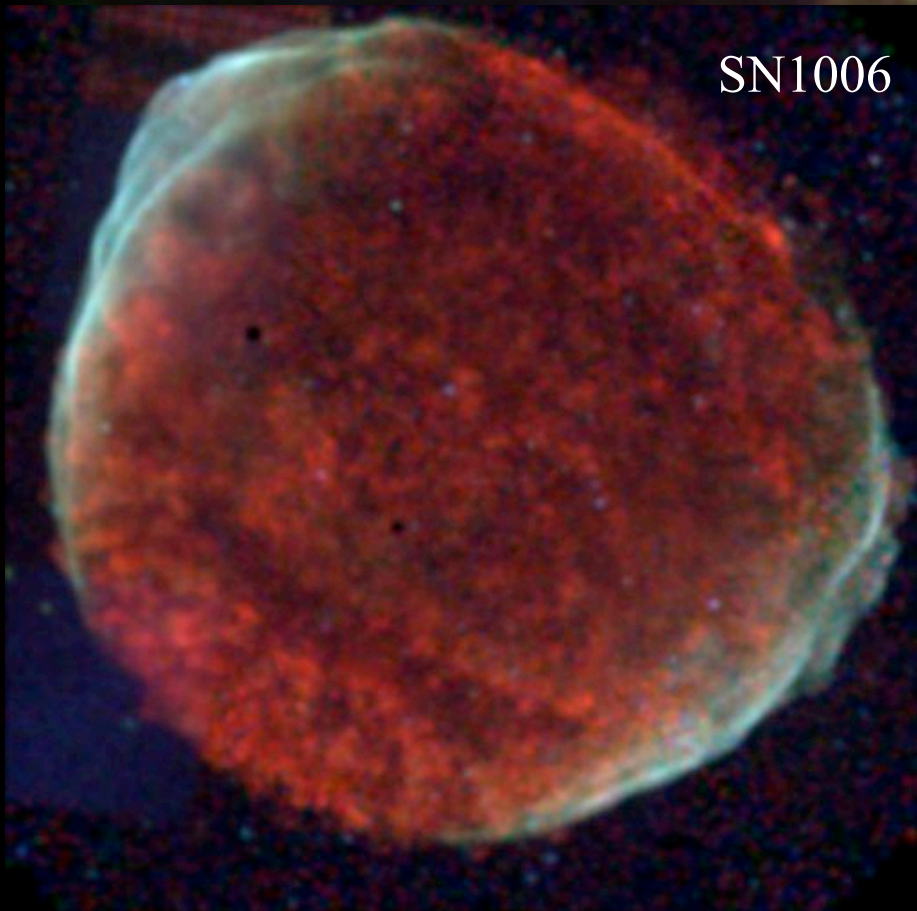
Fundamental differences between Type Ia and core-collapse supernovae :

- Type Ia:
- The whole star is disrupted by the explosion
 - The source of energy is nuclear fusion, predominantly the burning of C/O into ^{56}Ni
 - Most of the energy is in the form of heat (10^{51} erg)
- Type II/Ibc:
- The core of the star collapses into a neutron star
 - The source of energy is therefore gravity ($\sim GM^2/R_{\text{NS}} \sim 10^{53}$ erg)
 - Most of the energy released as neutrinos!
 - Only 1% converted to heat/kinetic energy!
 - Nuclear fusion: by-product/not source of the explosion



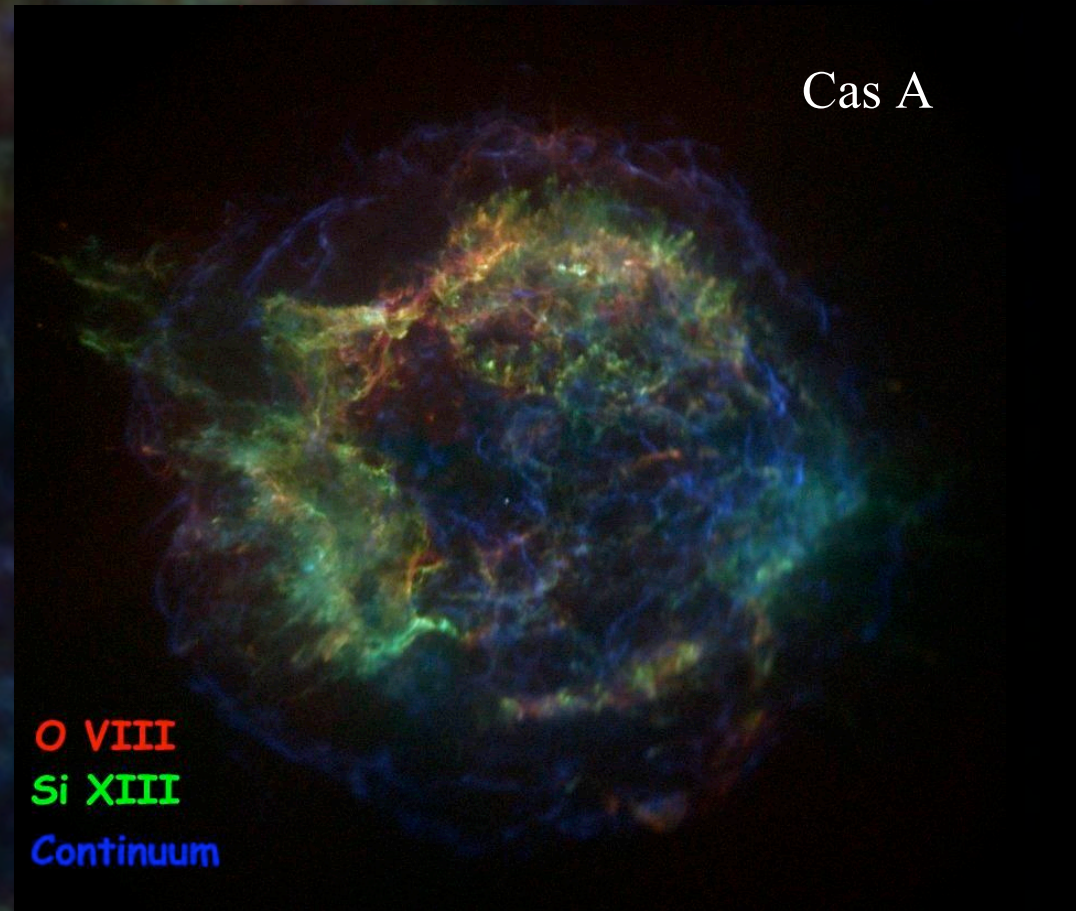
Supernova vs Supernova Remnants Types

Shell Types: Shell of shock heated gas



SN1006

Type Ia supernova
Shell Type SNR



Cas A

Core-collapse supernova (Type Ib)
Shell Type SNR

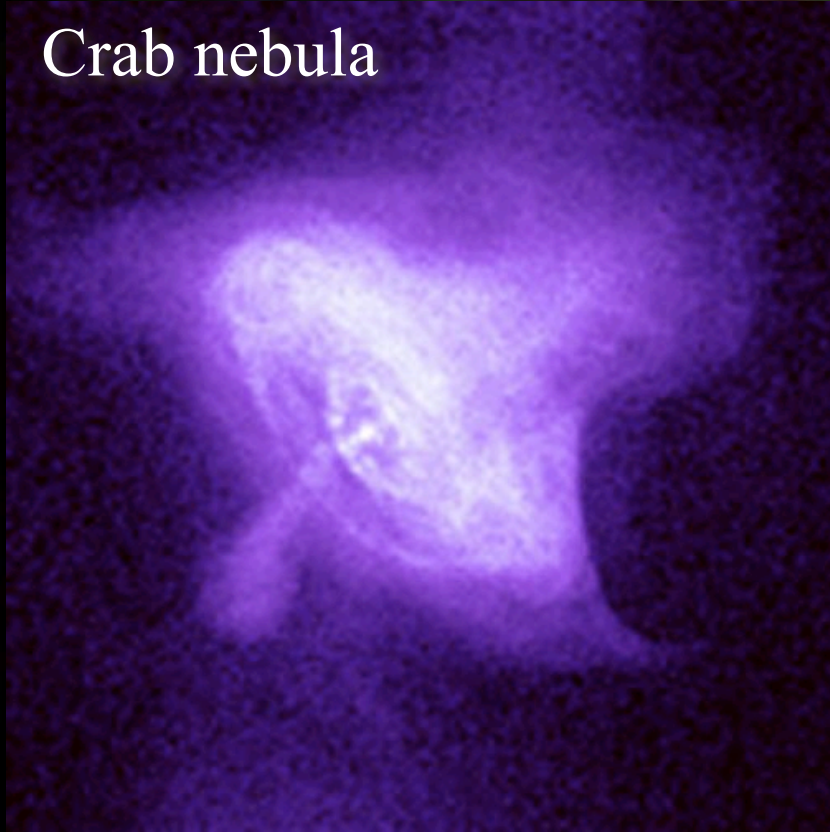


Supernova vs Supernova Remnants Types

Pulsar Wind Nebula (PWN) dominated SNR or Plerions

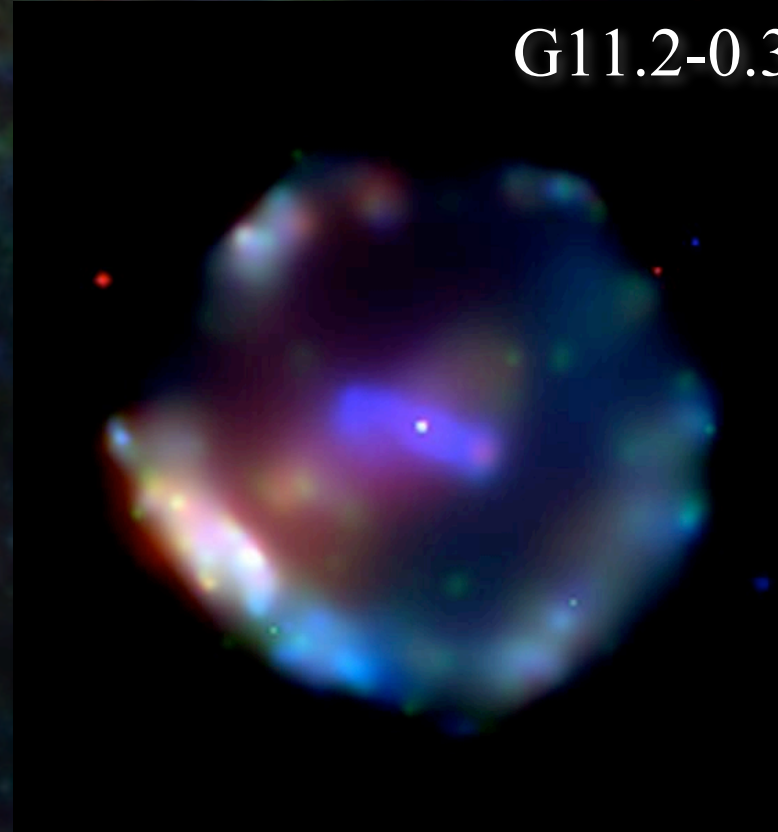
PWN: X-ray synchrotron emission from relativistic electrons

Crab nebula



Core-collapse supernova
Plerion

G11.2-0.3



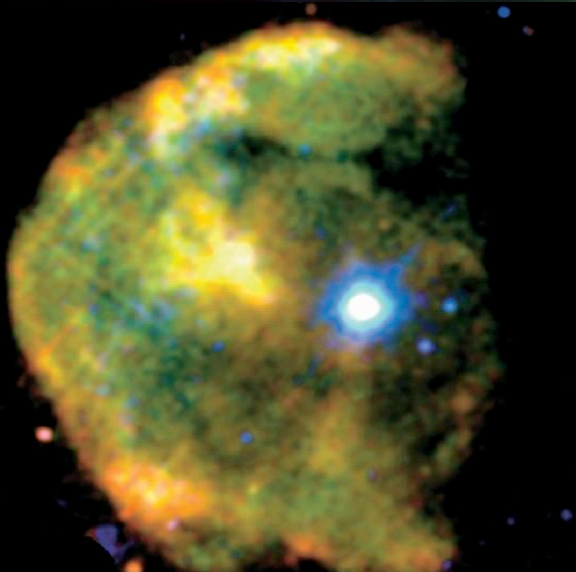
Core-collapse supernova
Composite (pwn+shell)



The role of the neutron star

The appearance of a supernova remnant depends:

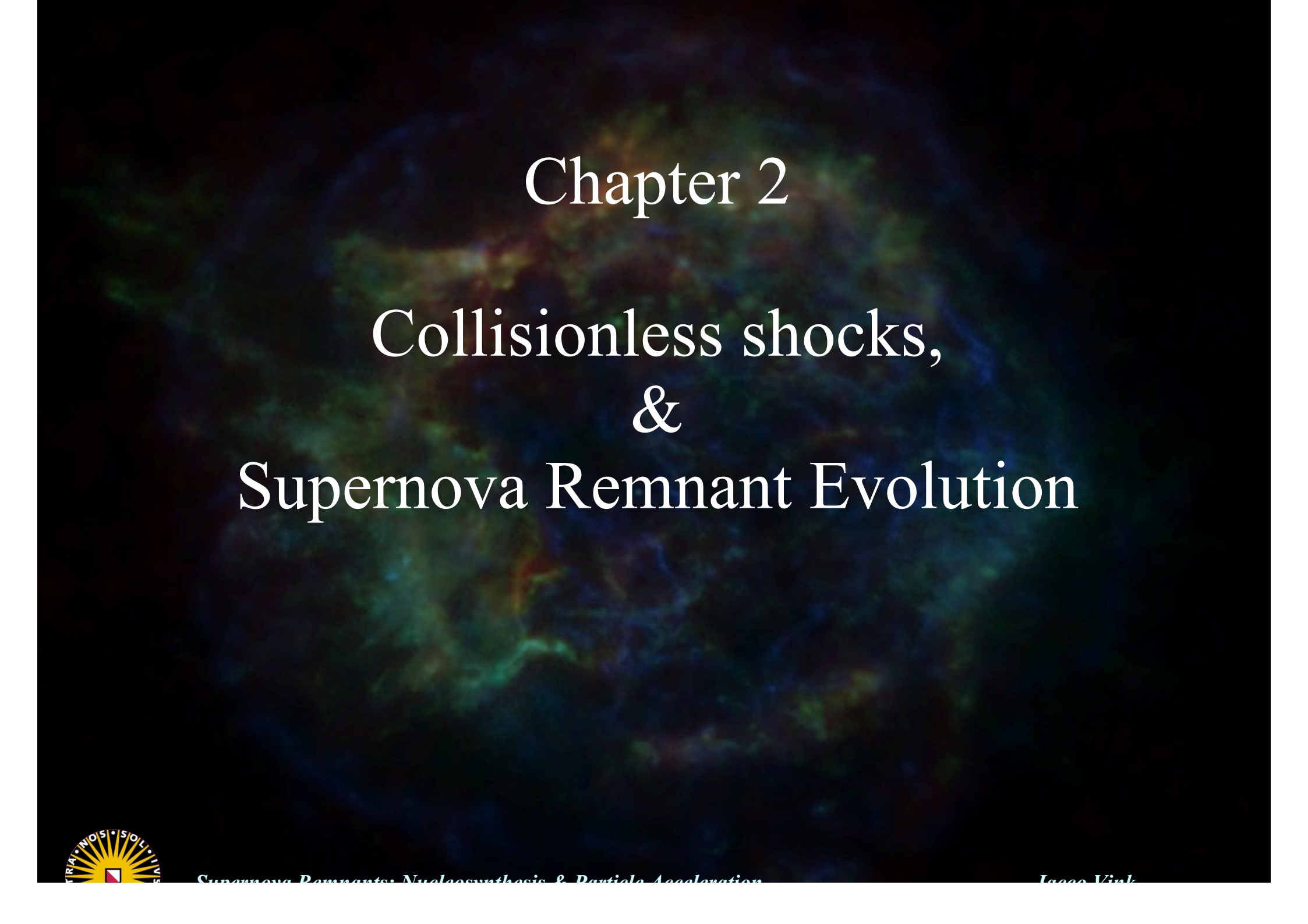
- The interstellar/circumstellar medium: density, clouds
- The supernova type:
 - Type Ia → shell type remnant
- Core-collapse SNR morphology depends on stellar remnant:
 - Black Hole (?), weak neutron star → shell type remnant
 - energetic pulsar → large pulsar wind nebula with shell
 - crab nebula → something special (?):
 - energetic pulsar, but no shell (weak explosion?)



CTB 109:

Asymmetric: one sided cloud interaction

Not a plerion, but bright point source: a magnetar



Chapter 2

Collisionless shocks, & Supernova Remnant Evolution



SNR Shocks

- Whenever matter moves through a medium with a speed higher than the sound speed a shock forms
- The shock consists of a sharp boundary ($1 \sim$ atom free mean path) over which temperature increases
- The plasma is very tenuous (1 particle/ cm^3)
- Hence, not many colliding particles:
mean free path for Coulomb collisions $>$ size of shell
- Hence, the name collisionless shocks
- Instead particles are heated by plasma waves
- Behind shock: few collisions, atoms not immediately ionized



Shocks

- Conservation laws: mass, momentum and energy conservation:

Use system in which shock is at rest

$$\rho_1 v_1 = \rho_2 v_2$$

$$(\rho_1 v_1) v_1 + p = (\rho_2 v_2) v_2 + p$$

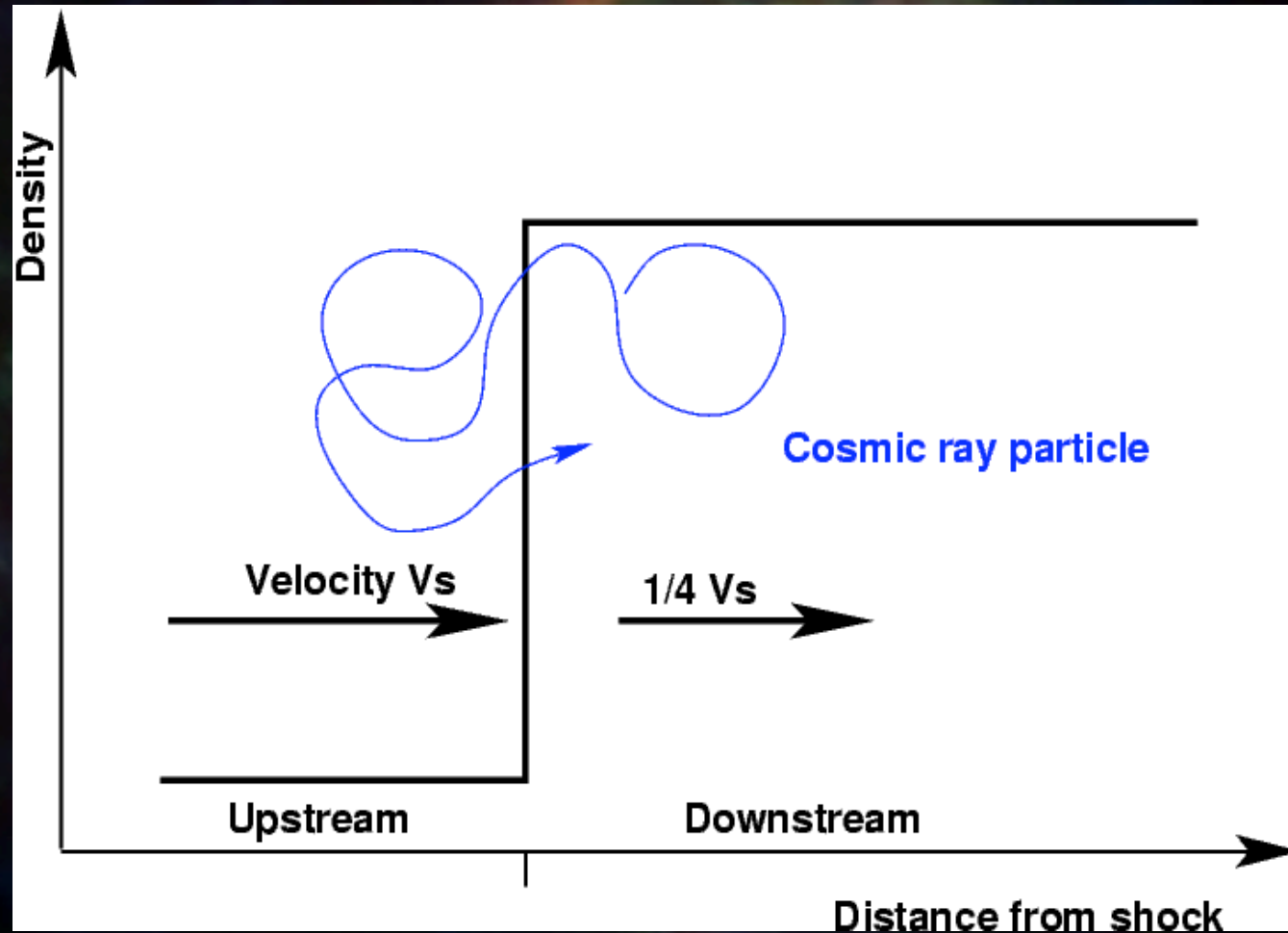
$$(1/2 \rho_1 v_1^2 + u) v_1 = (1/2 \rho_2 v_2^2 + u) v_2$$

internal energy $u = p/(\gamma - 1)$, $\gamma = 5/3$ for monatomic gas

- Simplification: heat sinks (cosmic ray acceleration!), magnetic fields, and radiation losses not taken into account.
- For strong shocks ($M \rightarrow \infty$) one finds:
 - $\rho_2 / \rho_1 = (\gamma + 1) / (\gamma - 1) = 4$, implying $v_2 = 1/4 v_s$
 - $kT_2 = 2(\gamma - 1)(\gamma + 1)^{-2} m v_s^2 = 3/16 m v_s^2$, with m particle mass
- Should one consider different temperatures for each particle?
Or can we take the average $m = 0.6 m_p$?



Sketch of shock structure



The Evolutionary Phases of SNRs

Traditionally four evolutionary phases are recognized.

I Free expansion phase: $M_{\text{ejecta}} > M_{\text{swept}}$
 $V_s = R_s/t$

II Adiabatic phase (no radiation losses),
also called Sedov phase:

$$M_{\text{ejecta}} < M_{\text{swept}}$$

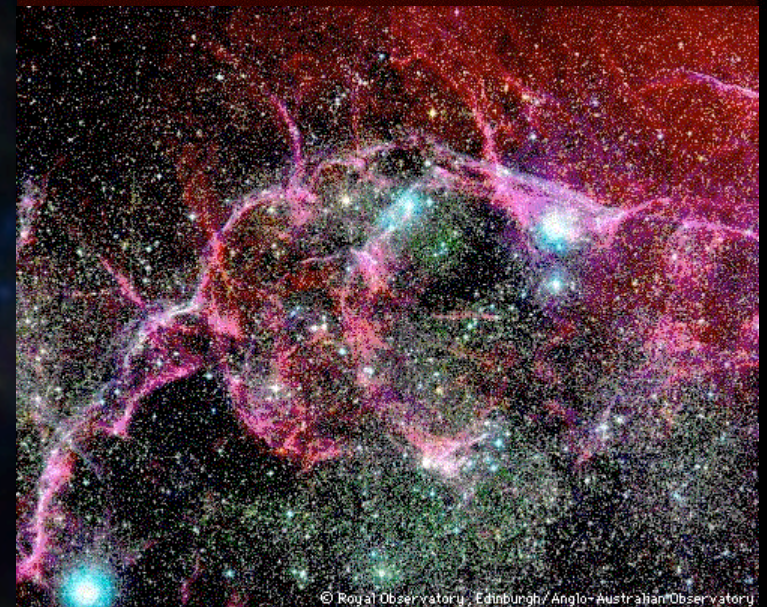
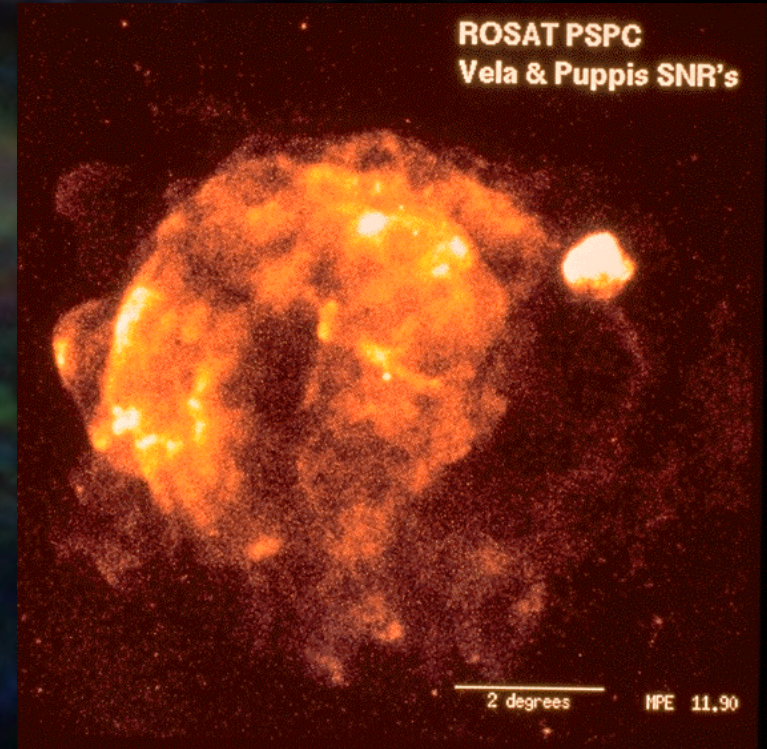
$$V_s = 2/5 R_s/t \quad (\text{ISM})$$

$$V_s = 2/3 R_s/t \quad (\text{CSM})$$

III Radiative losses important,
no conservation of energy,
conservation of momentum.
Characterized by bright optical emission

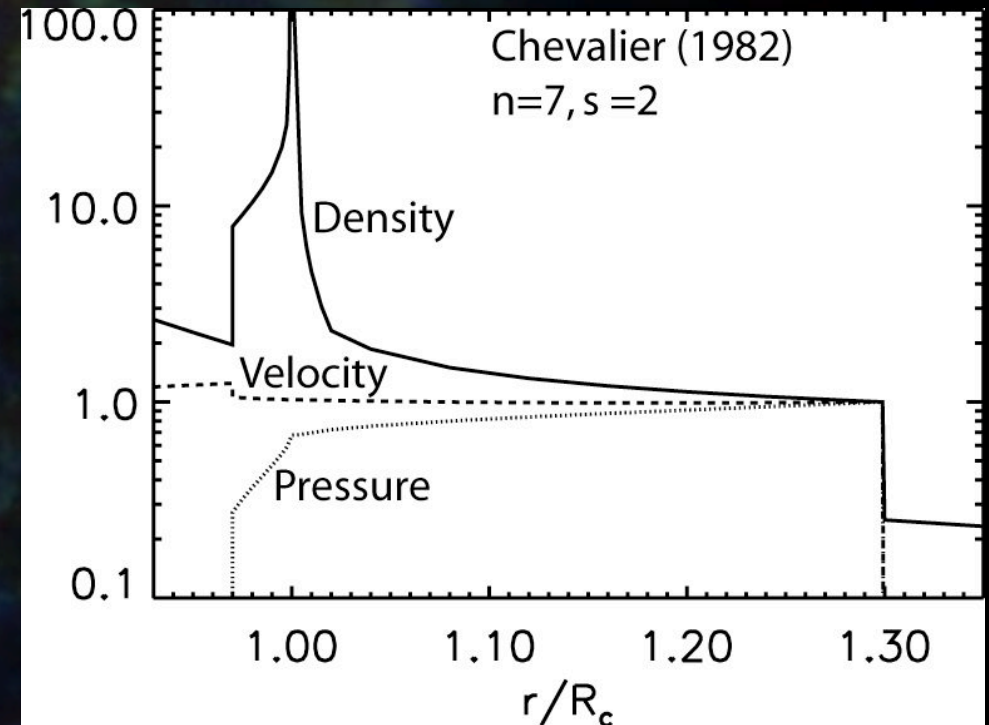
IV Dissappearance phase $V_{\text{shock}} \rightarrow V_{\text{sound}}$

These are useful terms to speak about SNRs,
But reality often more complicated!



The Structure of Young SNRs

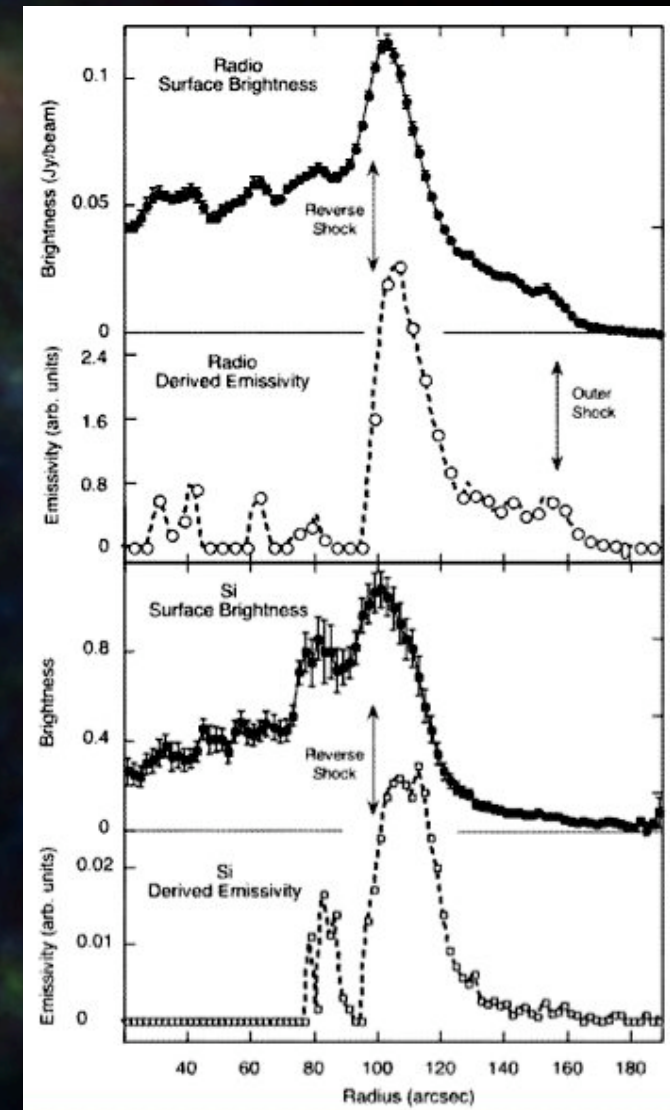
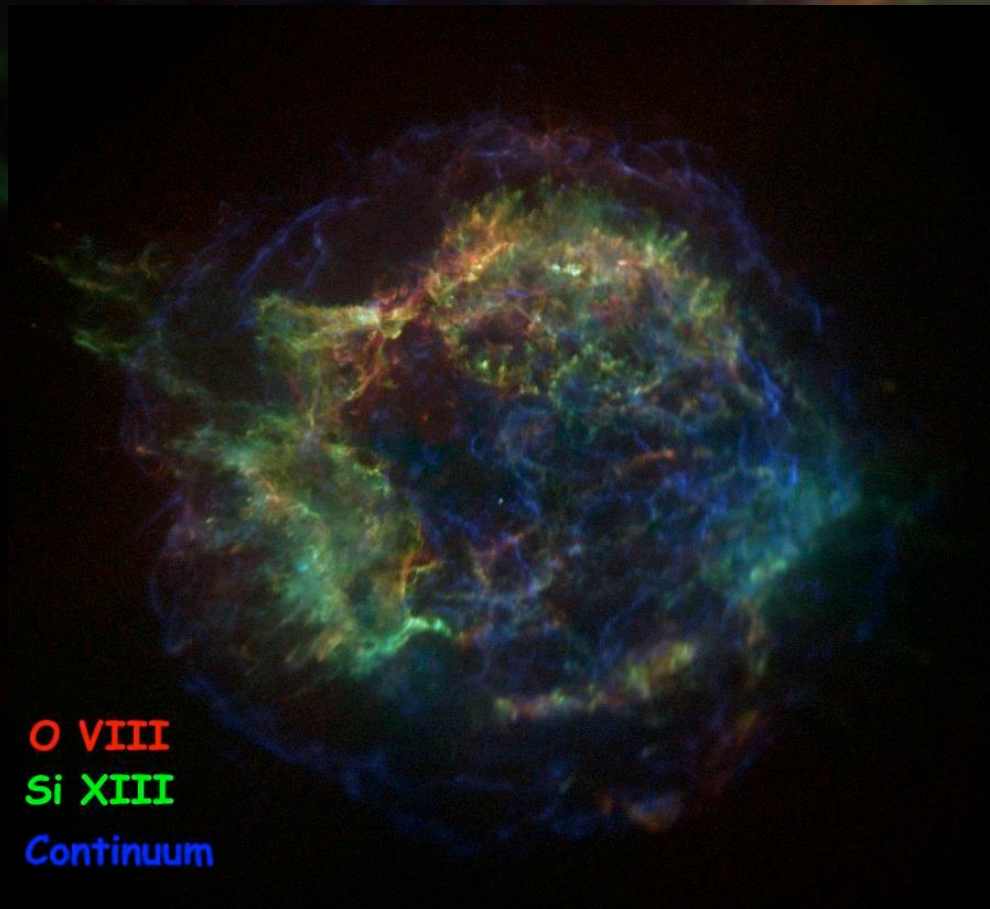
- After supernova explosion gas cools adiabatically due to expansion
- May lead to dust formation
- Fastest material shocks CSM/ISM
- Hot shell forms with high pressure
- High pressure causes a shock into the freely expanding ejecta:
The Reverse Shock
- So young SNRs have two shocks:
 1. Forward shocks heating ISM/CSM
 2. Reverse shock heating ejecta



Self-similar model by Chevalier (1982)



The Reverse Shock in Cas A



Gotthelf et al. 2001

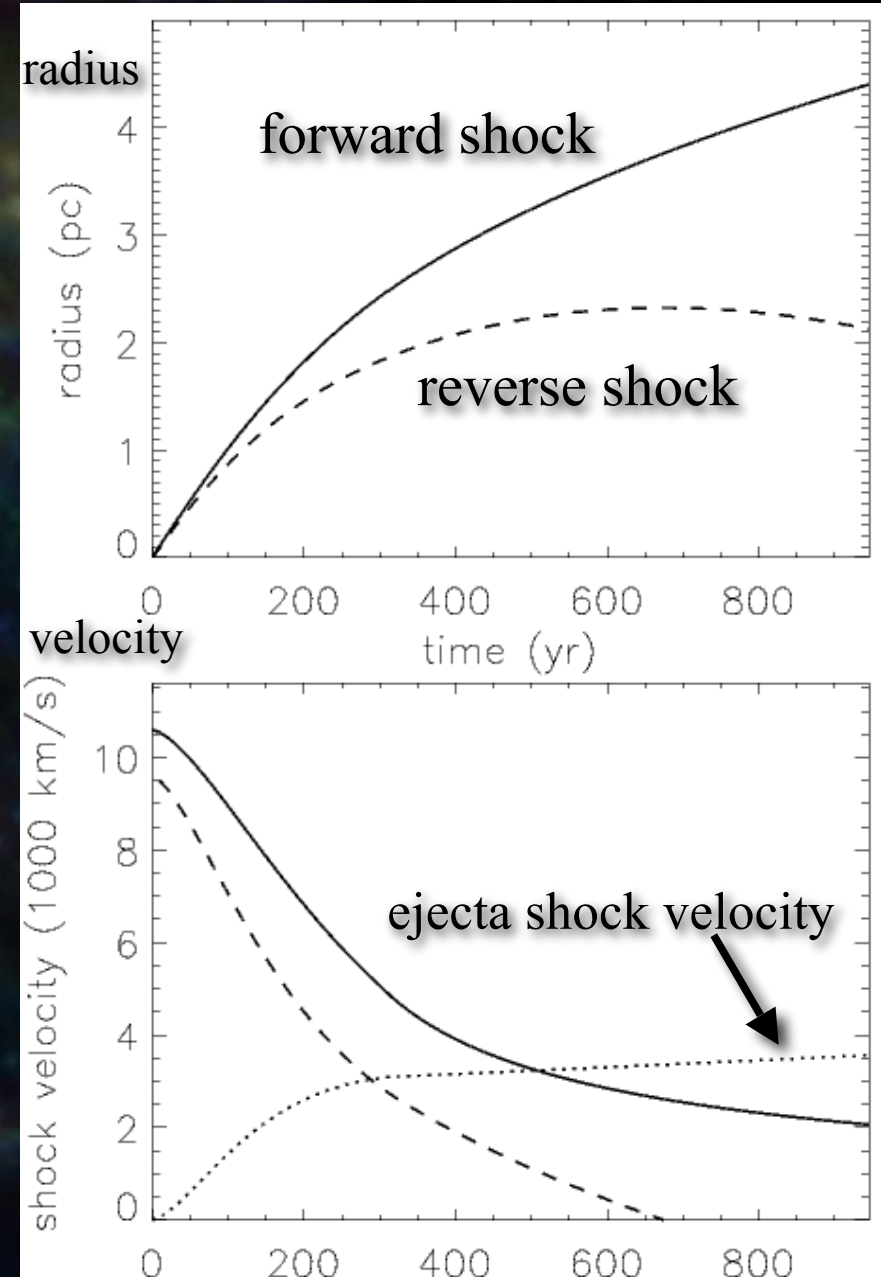


Forward & Reverse Shock Evolution

Truelove & McKee models for evolution

Connects smoothly the free expansion with Sedov phase

Note the reverse shock trajectory:
Moves outward and then inward,
eventually reaching the center



Truelove & McKee (1999)



The Sedov Evolution Model

Energy conservation implies: $E_{\text{tot}} = \text{Volume} (u + 1/2 \rho v_2^2)$

Recall $kT_2 = 2(\gamma-1)(\gamma+1)^{-2} m v_s^2$, write $u = \rho T = \alpha \rho (dR_s/dt)^2$

Assume thin shell with $\text{Volume} = f 4\pi/3 R_s^3$, velocity $v_2 = \beta dR_s/dt$

Rewrite the energy equation as

$$4\pi/3 f R_s^3 (\alpha + 1/2 \beta) \rho (dR_s/dt)^2 = E_{\text{tot}}$$

Absorbing all constants (same for all SNRs) into one constant K we get

$$K R_s^3 \rho (dR_s/dt)^2 = E_{\text{tot}}$$

$$R_s^{3/2} dR_s/dt = (K^{-1} E_{\text{tot}} / \rho)^{1/2}$$

Sedov solution

$$R_s = (K' E_{\text{tot}} t^2 / \rho)^{1/5} \quad (K' = 2.026)$$

$$V_s = 2/5 R_s / t$$



Chapter 3

Thermal X-ray Radiation from Supernova Remnants



The Nature of the Thermal X-ray emission

Recall: $kT_2 = 2(\gamma-1)(\gamma+1)^{-2} m v_s^2 = 3/16 m v_s^2$

Typically shock velocities are

- 5000 km/s for young SNRs,
- 200 km/s for old SNRs (radiative phase)

We have: $kT = 1.1 (v_s/1000 \text{ km/s})^2 \text{ keV}$,

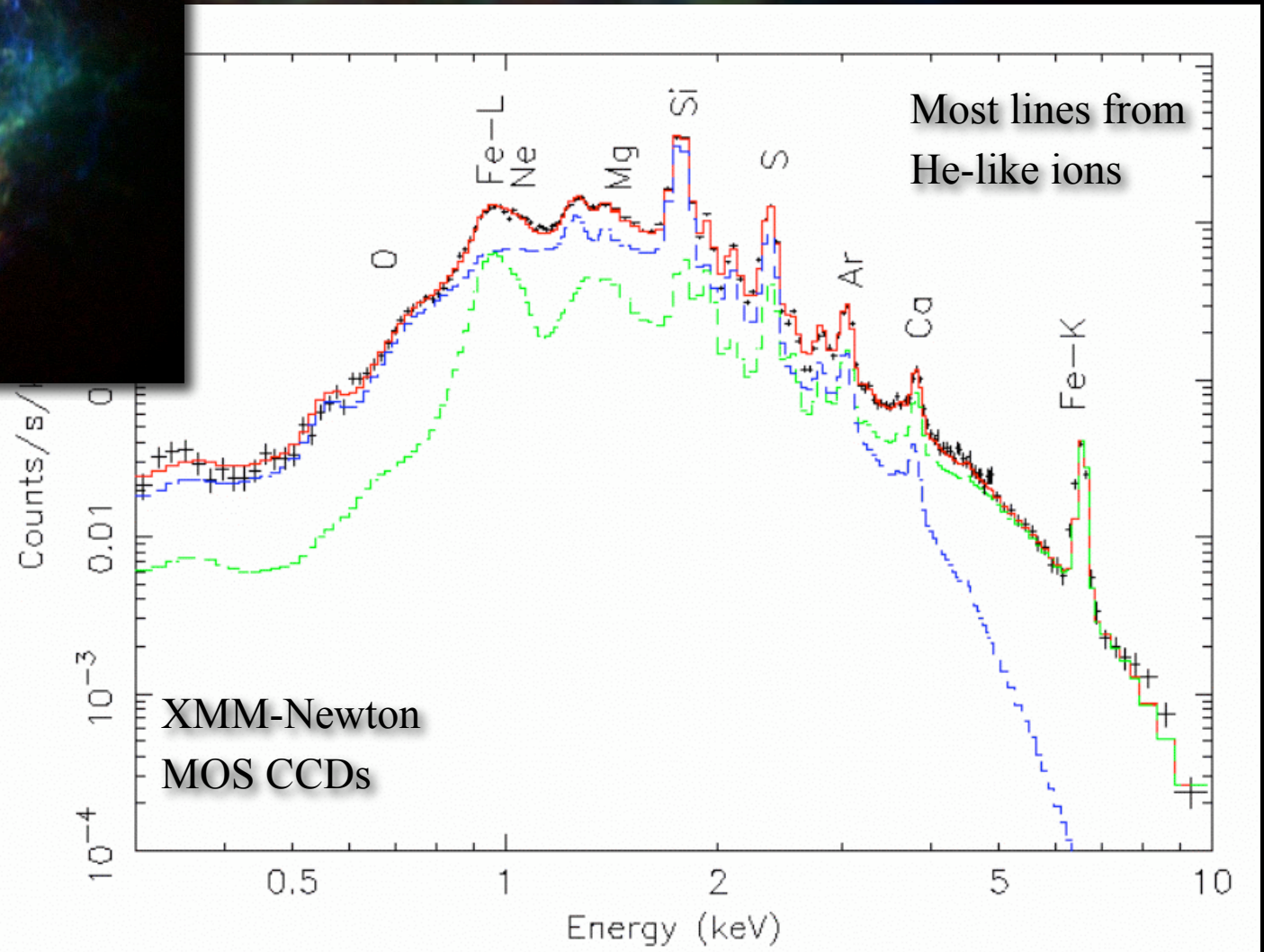
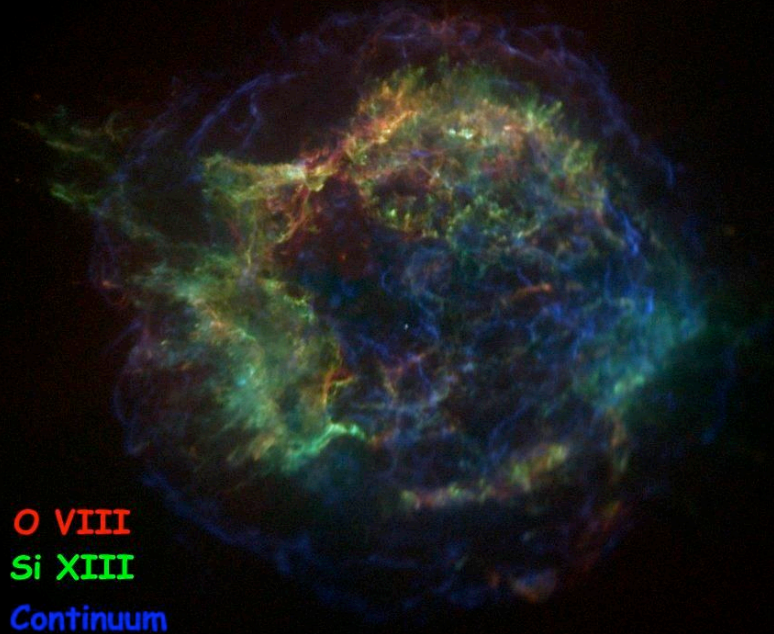
Temperatures as high as 25 keV are expected (but not observed!)

Radiation expected:

- For a size of 10 pc and $n=1 \text{ cm}^{-3}$, we have $N_H < 10^{20} \text{ cm}^2$
- Radiation must therefore be optically thin
- Continuum process: mostly bremsstrahlung
- Additional processes: free-bound emission, two photon continuum
- Dominating radiation: line radiation

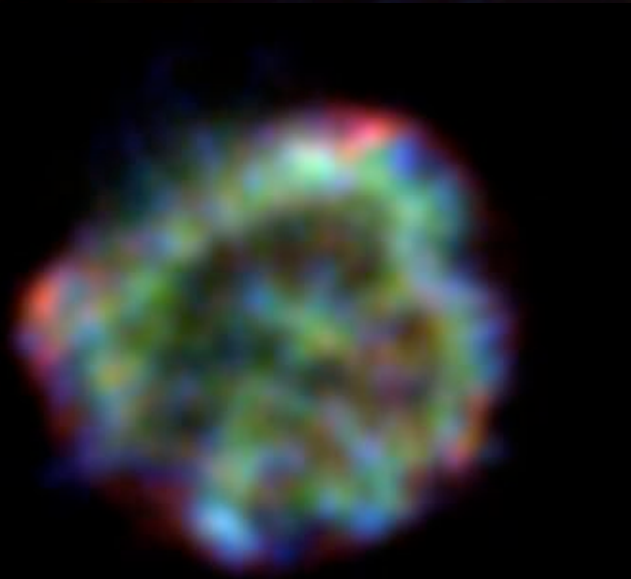


A Typical X-ray Spectrum (Cas A)



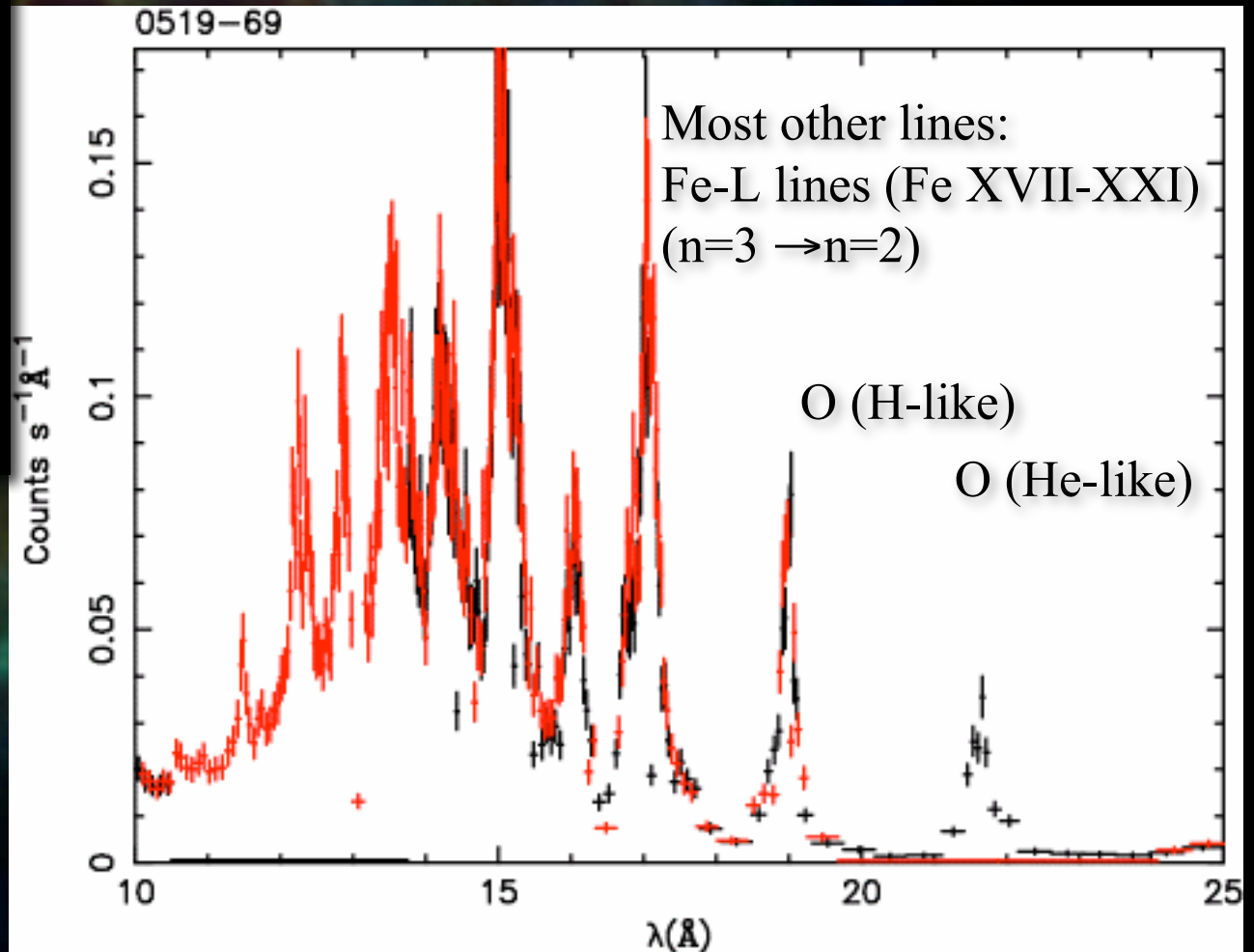
A High Resolution Spectrum

LMC SNR 0519-69
(Type Ia remnant)



Chandra

XMM-Newton
Reflection grating
(RGS)



The Ionization Balance

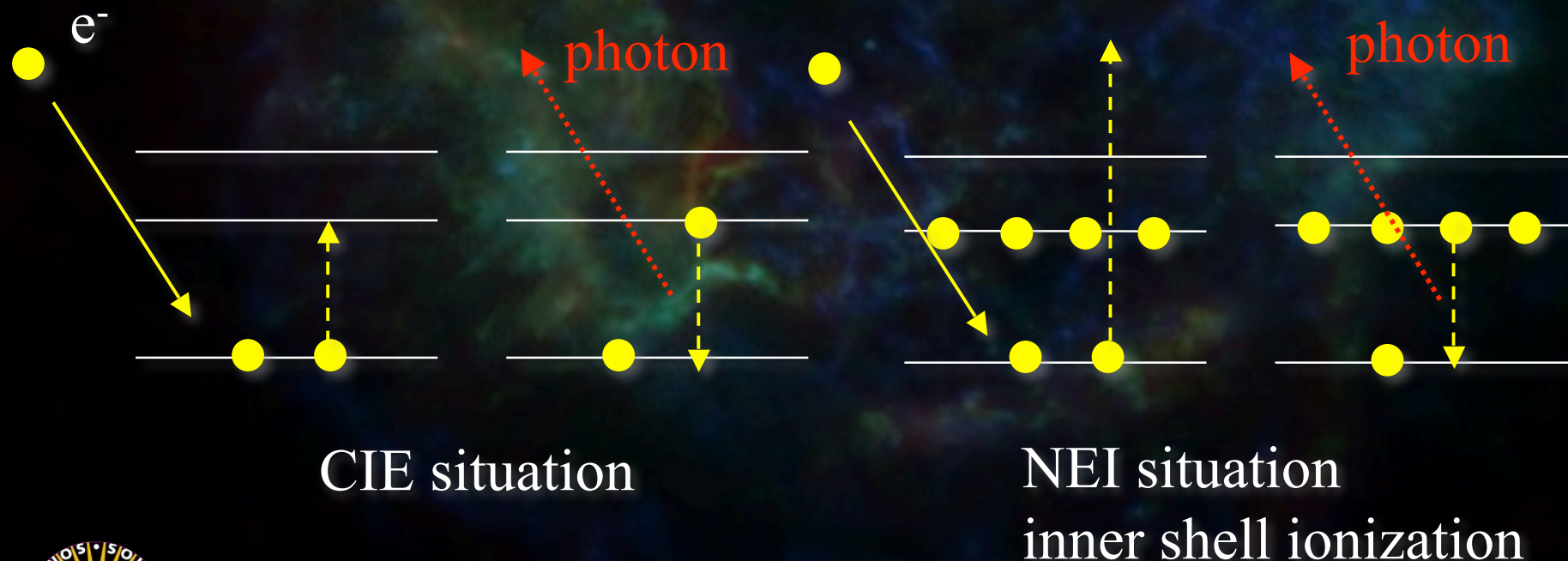
What determines the ionization state of an atom in a hot gas?

- Ionization rate
- Recombination rate (direct + dielectronic recombination)
- Ionization balance (coupled differential equations):
$$\frac{dN_i}{dt} = + n_e C_r(T, i+1) N_{i+1} + n_e C_i(T, i-1) N_{i-1} \\ - n_e C_r(T, i) N_i - n_e C_i(T, i) N_i$$
with n_e electron density,
 C_r/C_i recombination/ionization rate coefficients (σv_e)
- For equilibrium ionization demand $dN_i/dt = 0$
(Collisional Ionization Equilibrium, CIE)
- Density in SNRs so low that $dN_i/dt \neq 0$
(i.e. SNR characterized by Non Equilibrium Ionization, NEI)
- In what state it is depends on $n_e t$ ($\approx \int n_e dt$)
- Typically needed for equilibration: $n_e t = 10^{12} \text{ cm}^{-3} \text{ s}$



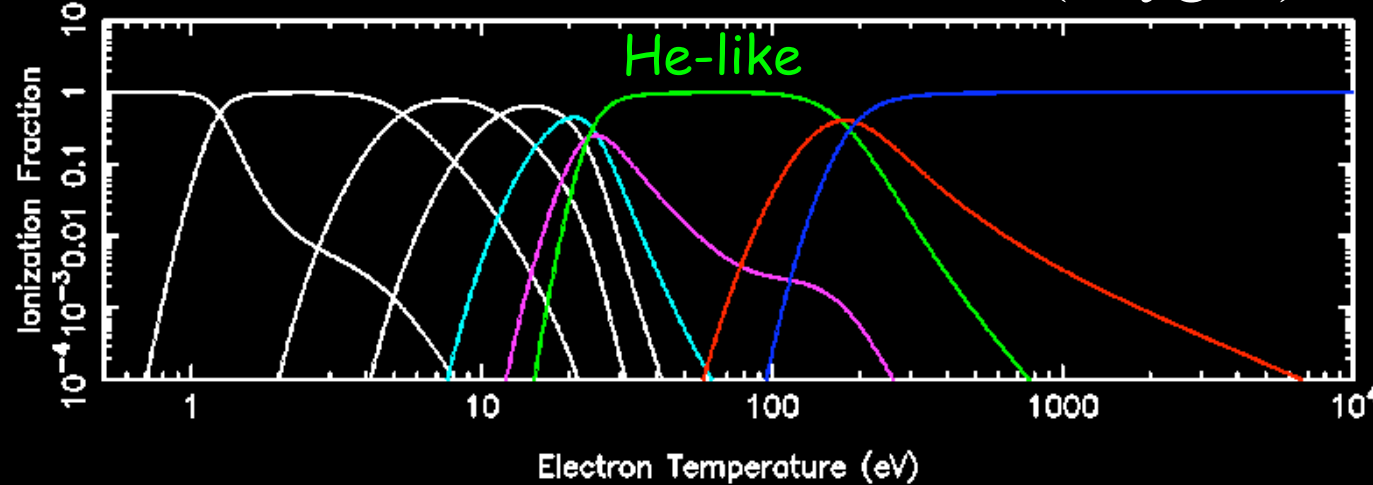
The Effects of NEI

- One observes lines from ion states that in CIE indicate a lower kT
- I.e. a mismatch between continuum and ionization “temperature”
- Since hot electrons co-exist with low ionization states one has more “inner shell ionizations”, resulting in different line energies
- After determining n_e one can estimate a rough age from $n_e t$

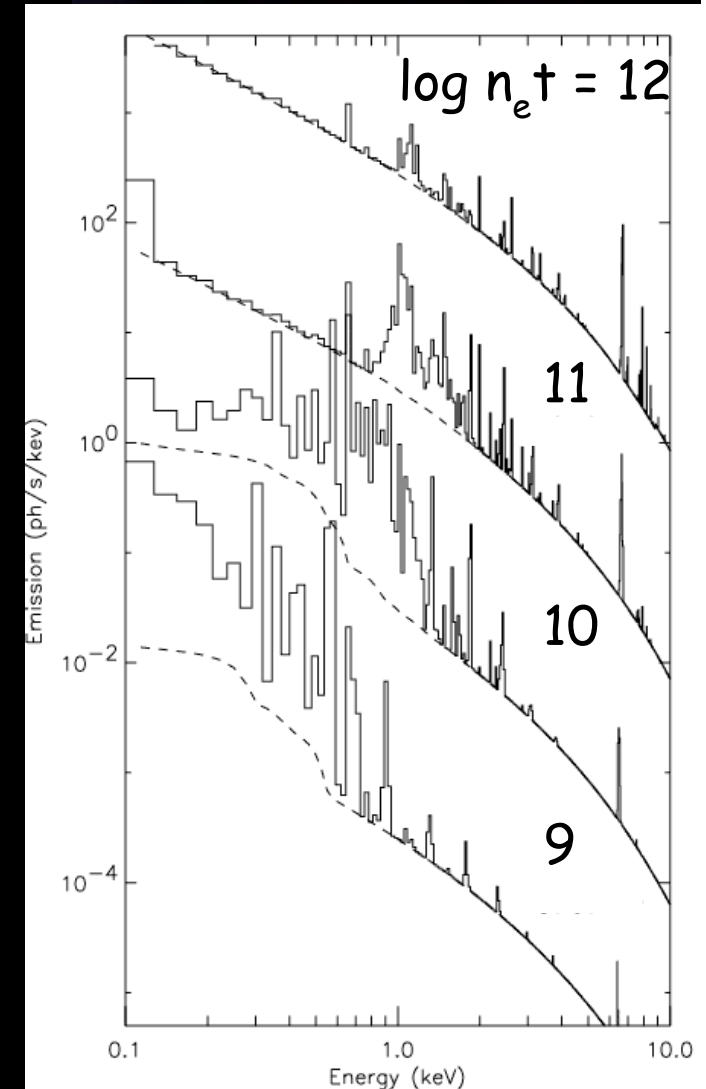
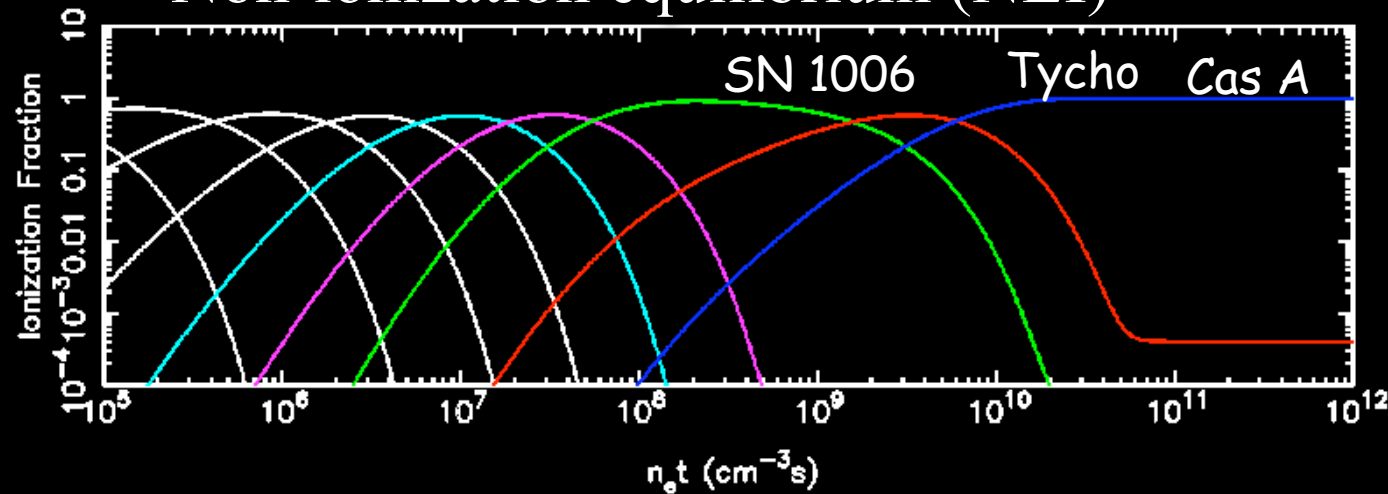


Non-Equilibrium Ionization (NEI)

Collision Ionization Equilibrium (oxygen)



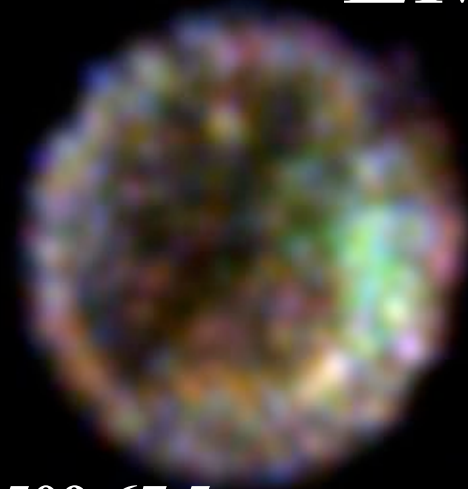
Non-ionization equilibrium (NEI)



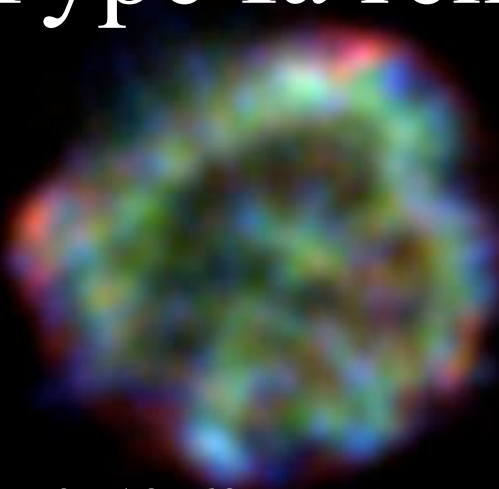
Ionization state depends on kT and $n_e t$



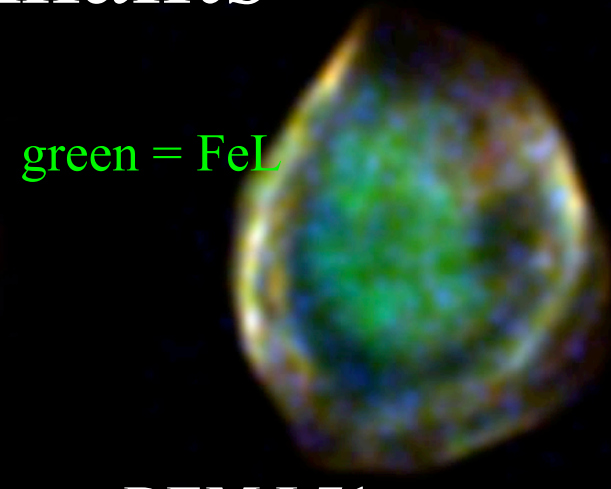
An (ionization) age sequence LMC Type Ia remnants



SNR 0509-67.5

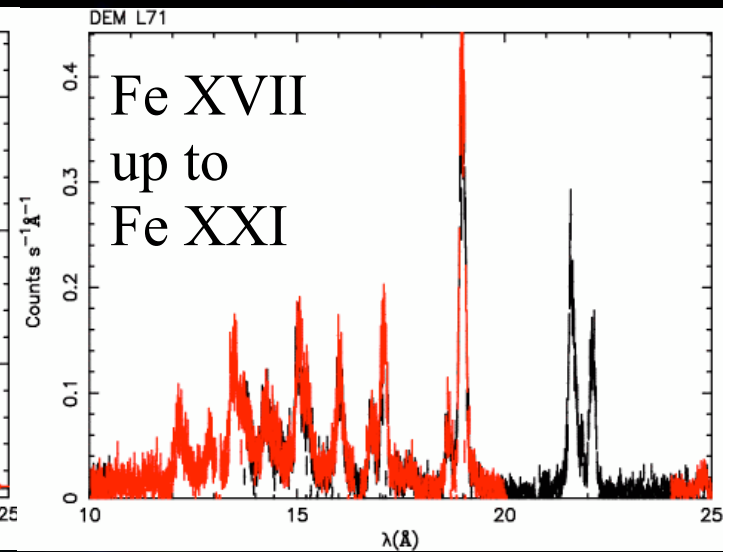
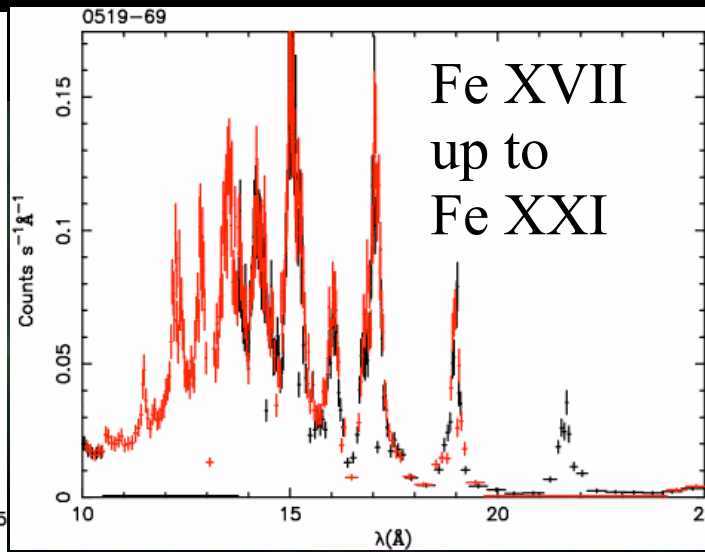
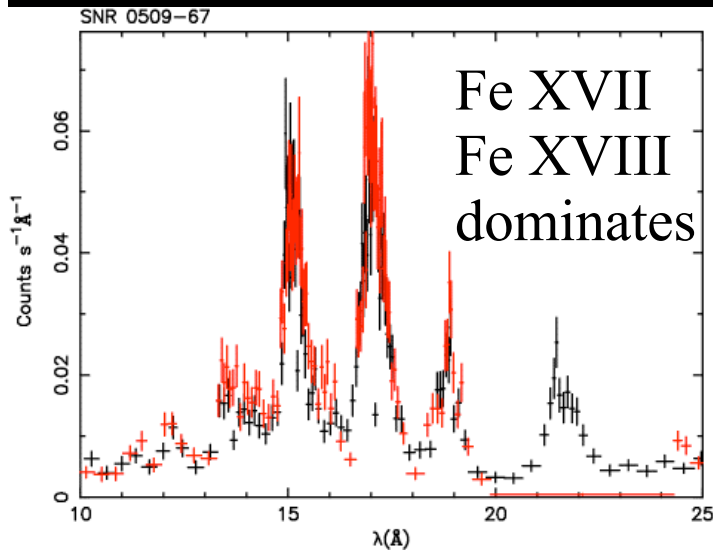


SNR 0519-69



DEM L71

green = FeL



Warren et al. 2004
Vink, et al. (in preparation)

Rakowski et al. 2003
van der Heyden et al. 2003

(Chandra images/XMM-RGS spectra)



Chapter 4

An application
of what we have learned so far



Determining the explosion energy

An application of what we have learned

Remember the following equations

- Shock physics: $kT_2 = 3/16 m v_s^2$ (1)

- Sedov solution: $R_s = (2.026 E_{\text{tot}} t^2 / \rho)^{1/5}$, $V_s = 2/5 R_s / t$ (2)

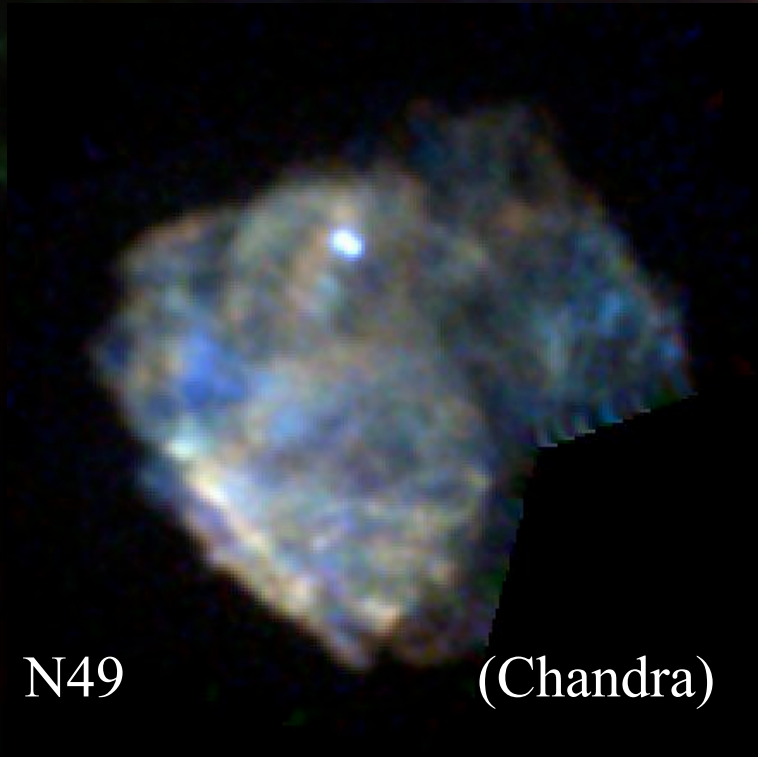
- To determine density, use the emission measure: $\int n_e n_H dV$ (3)
(determines spectral normalization, see e.g. xspec)

To determine energy:

- Measure R_s (X-ray image) and kT (spectrum) $\rightarrow V_s \rightarrow (2) t$ (age)
- From emission measure and volume $\rightarrow \rho \rightarrow (2) E_{\text{tot}}$
- System overdetermined: $\rho + n_e t \rightarrow$ independent measurement of t

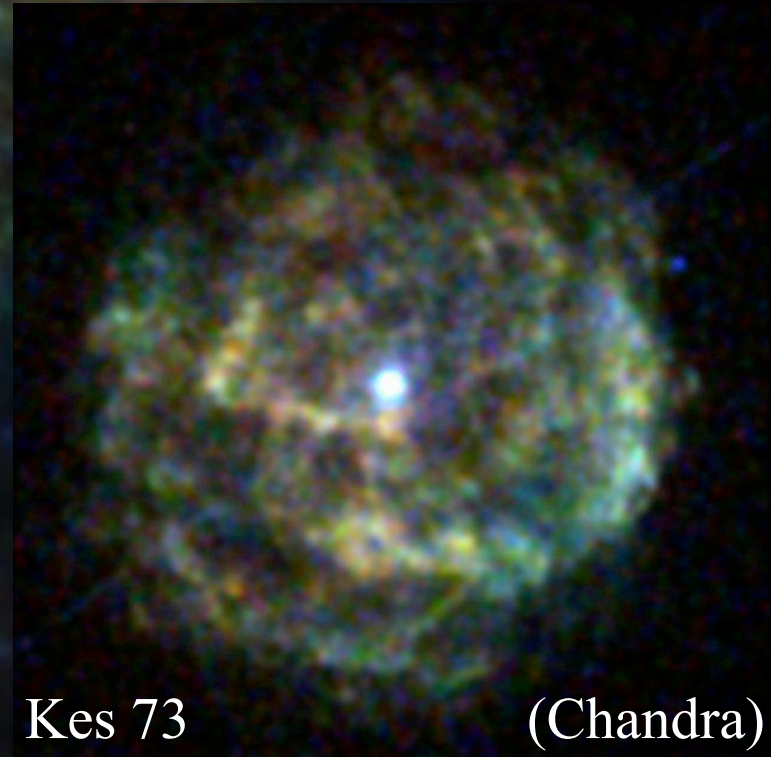


The Energy of N49 and Kes 73



N49

(Chandra)



Kes 73

(Chandra)

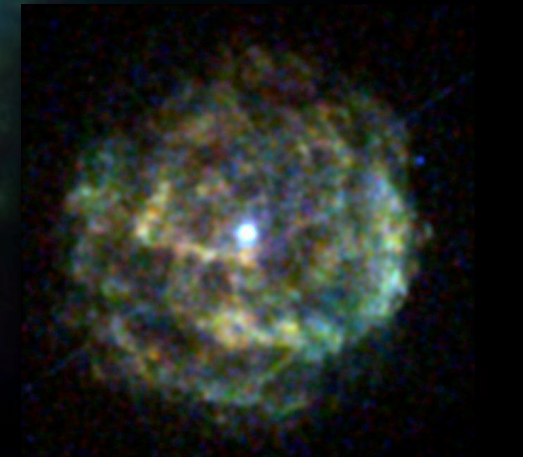
Both SNRs contain a magnetar: SGR0526-66, 1E1841-045

Vink & Kuiper
astro-ph/0604187



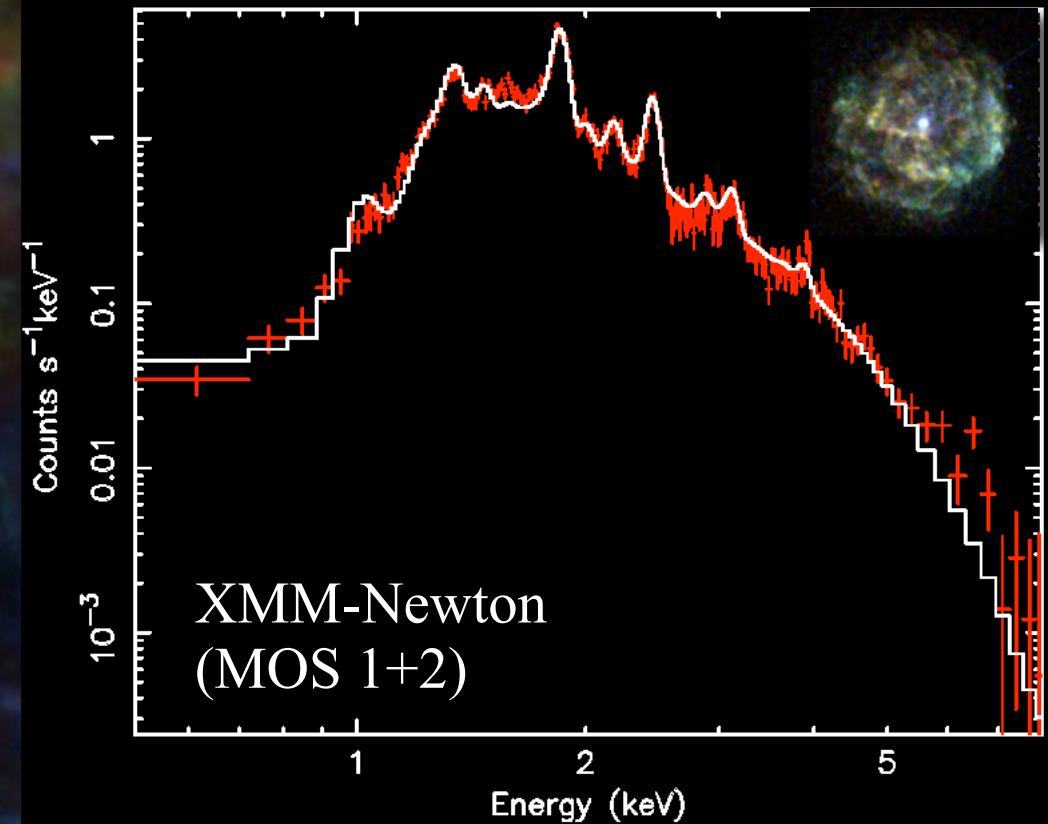
Why you should care about their Energy

- According to one theory (Duncan & Thompson 1993) magnetars form through magnetic field generation inside a rapidly spinning neutron star ($P \sim 1$ ms)
- Rotational energy for $P = 1$ ms, $E > 10^{52}$ erg
- Magnetic braking then very fast (100-1000 s)
- Energy injected into supernova ejecta \rightarrow hypernova (e.g. T. Thompson et al. 2005)
- Alternative theory:
magnetars form from high magnetic field progenitors (e.g. Ferrario & Wickramasinghe 2006)



Kes 73/1E1841-045

- Spherical morphology
- Distance $\sim 6\text{-}7.5$ kpc (HI abs.)
- Radius = 4 pc
- Spin down age: 4500 yr
- Spectral modeling:
 - $kT = 0.7$ keV $\rightarrow V_s = 800$ km/s
 - $n_e t = 4 \times 10^{11} \text{ cm}^{-3} \text{ s}$
 - $n_e = 4 \text{ cm}^{-3}$
 - mass = $29 M_{\text{sun}}$
 - no overabundances



$$E_0 = (0.5 \pm 0.3) \times 10^{51} \text{ erg}$$
$$t = 1300 \pm 100 \text{ yr}$$



N49/SGR 0526-66

- Non-spherical, SNR-cloud interaction

(e.g. Park et al. '03)

- Distance ~ 50 kpc

- Radius = 10 pc

- Spindown age: 1900 yr

- Connection SGR/SNR requires ~ 1000 km/s kick
(Gaensler et al '01)

- Spectral modeling indicates:

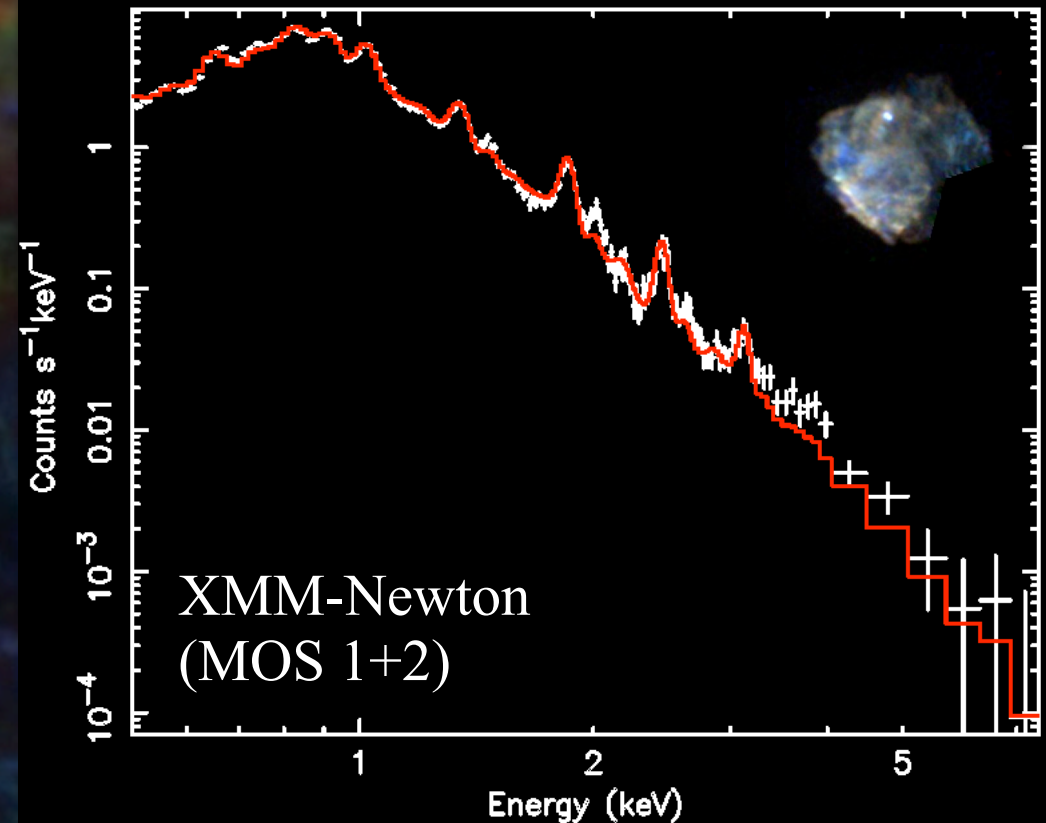
- $kT = 0.5$ keV $\rightarrow V_s = 700$ km/s

- $n_e t = 4 \times 10^{11} \text{ cm}^{-3} \text{ s}$

- $n_e = 3 \text{ cm}^{-3}$

- mass = $320 M_{\text{sun}}$

- no overabundances



$E_0 = (1.3 \pm 0.4) \times 10^{51} \text{ erg}$
 $t = 6300 \pm 2000 \text{ yr}$
(see also Hughes et al. '98)

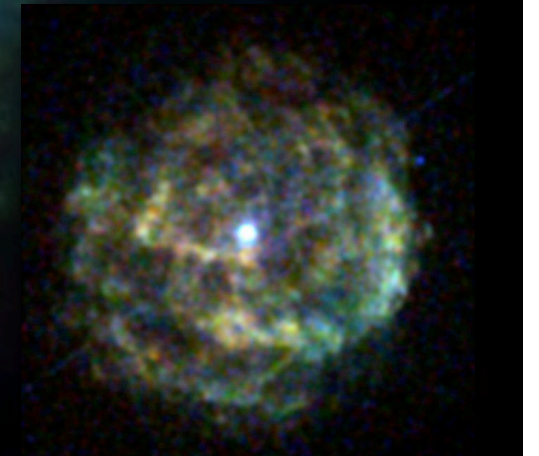
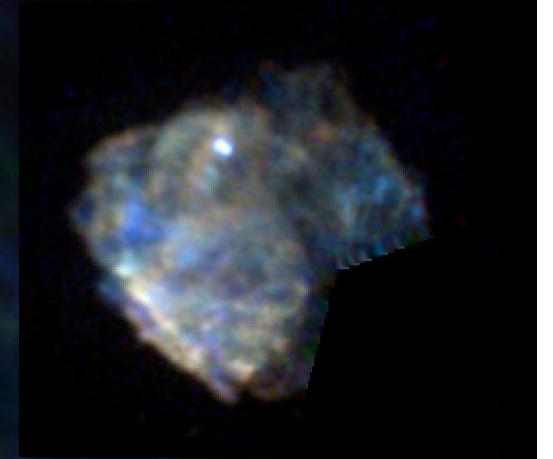


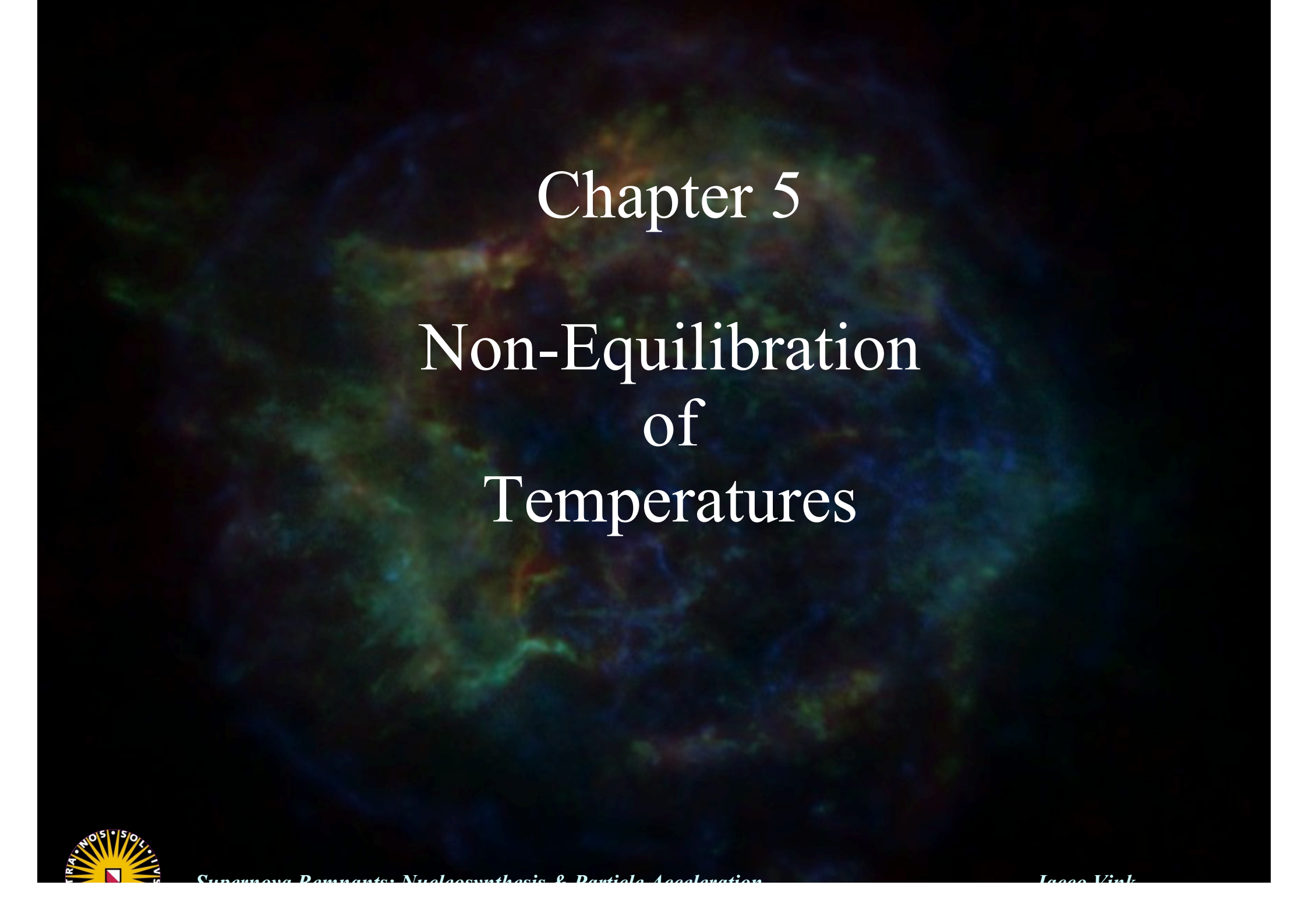
Conclusion for Kes 73, N49

- Creation of magnetar did not result in hypernova!
- Supports theory of high magnetic field progenitor
- However, if internal magnetic field high $> 5 \times 10^{16} \text{G}$ and surface field low $< 10^{14} \text{G}$

NS deformation may result in strong gravitational waves:
energy loss without imprint on SNR
(Stella et al. 2005)

- Does require lower B-field than currently observed





Chapter 5

Non-Equilibration of Temperatures



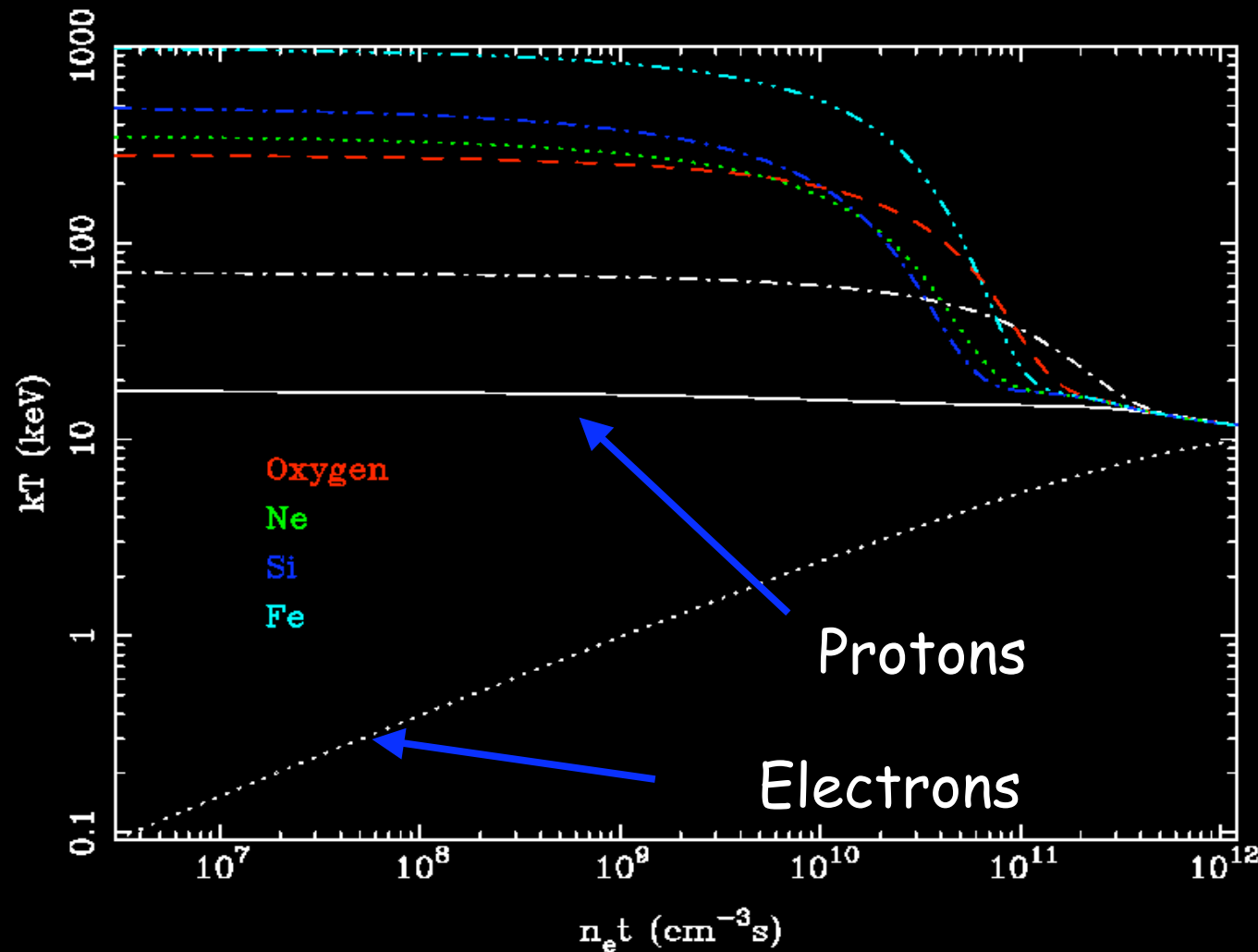
What is temperature?

- Temperature = the mean kinetic energy of the gas particles
- We speak of non-equilibration of temperatures
 - if the mean temperature of each type of particle (proton, electron, other ions) is different
 - or if the energy distribution is non-Maxwellian
- For shock heating, conservation of mass, momentum, energy demands (non-equilibration):
$$kT_{e,p,i} = 2(\gamma-1)(\gamma+1)^{-2} m_{e,p,i} v_s^2 = 3/16 m_{e,p,i} v_s^2 \quad (\text{for } \gamma = 5/3)$$
- Question: do plasma waves (collisionless shocks) give rise to equilibration or not ?
- For equilibration we replace $m_{e,p,i}$ by $\langle m \rangle \sim 0.6 m_p$
- $dE_{pe}/dt \propto n_e T^{-3/2}$ implies a time scale $n_e t$



Temperature Non-equilibration

Simplified plane parallel shock model, no equilibration:



Is this the reason that no SNR has been observed with $kT_e \sim 25$ keV?



How do we measure temperatures?

- X-ray continuum (bremsstrahlung) and line ratios:
gives only *electron* temperature
- Most of internal energy taken up by ions (protons)
- Measuring ion temperature: thermal line broadening
Problem: lines also broadened by bulk plasma motion
- Solution: measure line broadening at edge of remnant
→ bulk motions only in line of sight (no Doppler effect)
- Measurements of ion thermal line broadening done in:
 - optical from H-alpha (Raymond, Chevalier, Smith, Ghavamian c.s.)
 - UV (Raymond et al. 1996, Korreck et al. 2004)
 - X-ray with XMM-Newton (Vink et al. 2003)



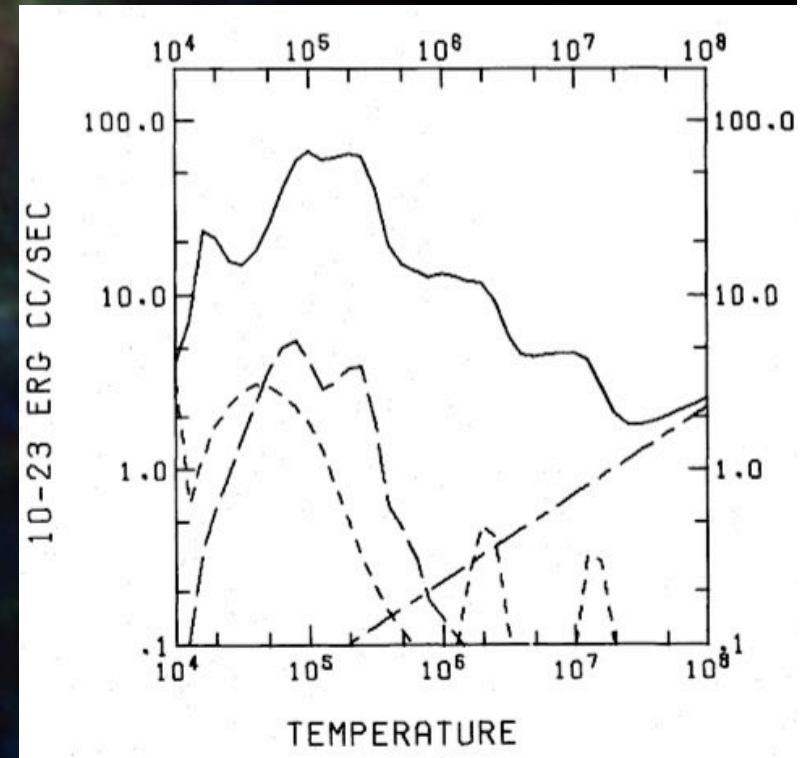
Non-radiative H α emission (a short digression to other wavelengths)

Radiative H α Emission

- For temperatures $<10^6$ K rapid cooling
- Meaning: rapid cooling for low V_s
- Runaway cooling: optical emission
- Bright H α filaments

Non-radiative H α Emission

- Partial neutral medium
- Brief moment (~ 1 month) hydrogen atoms remain neutral inside shocked region
- Line emission due to two processes:
 1. excitation \rightarrow narrow H α
 2. charge exchange \rightarrow broad H α \rightarrow direct measurement of proton kT (electrons switches from hot proton to cool H)

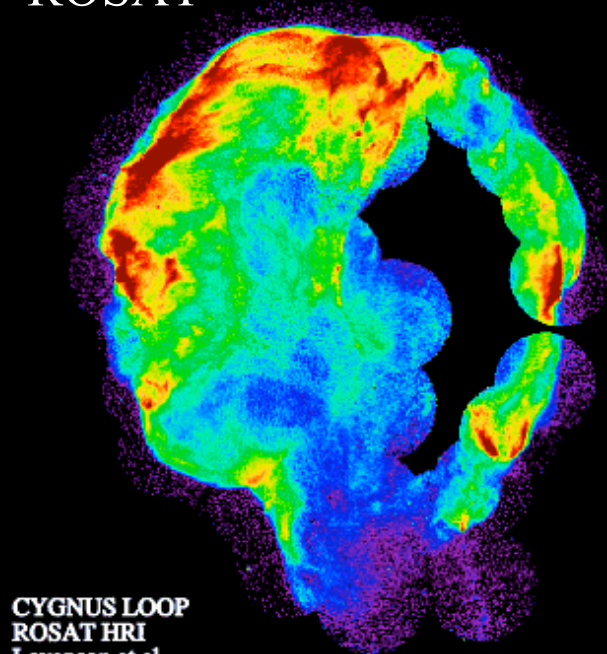


Raymond et al. '76

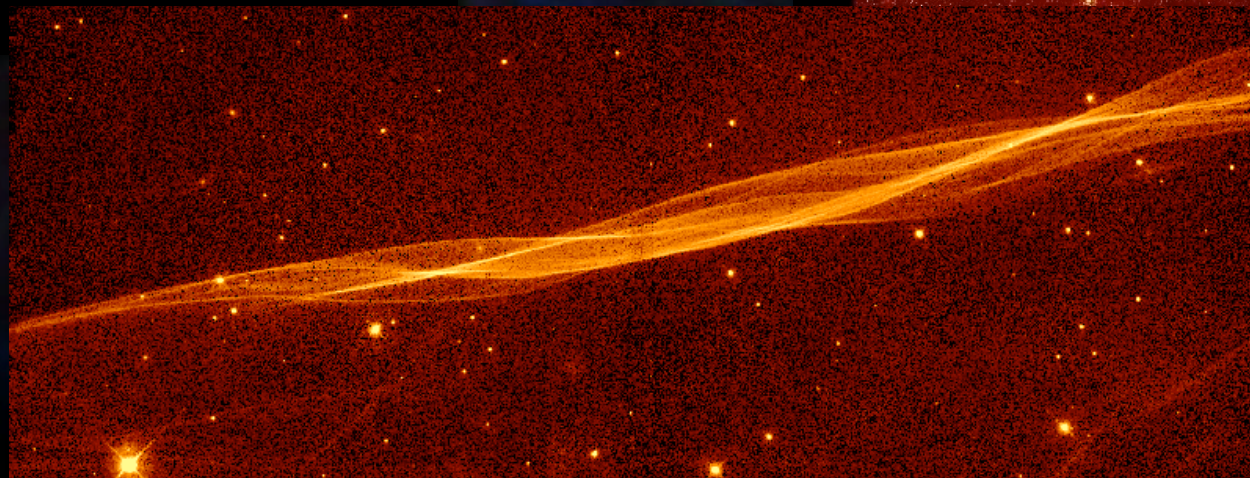
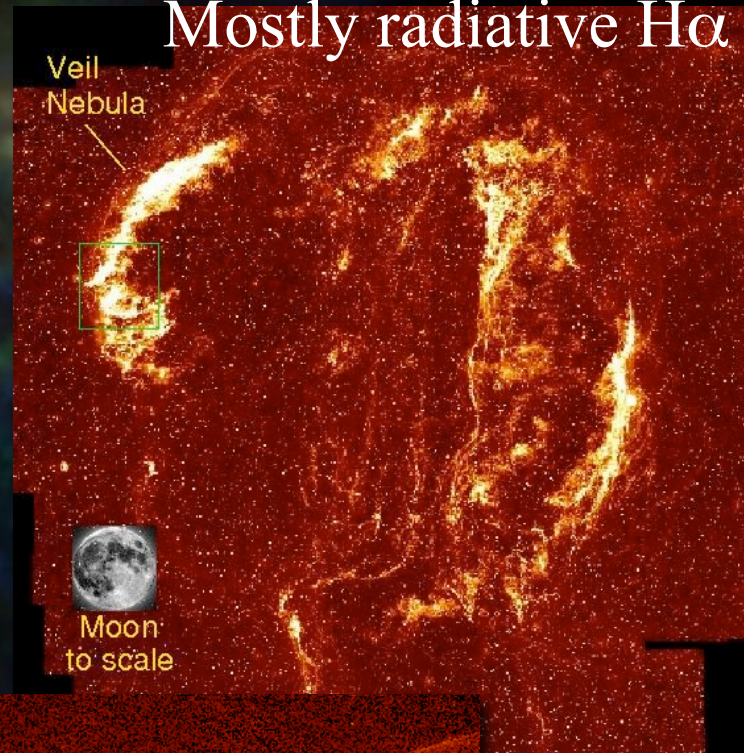


Examples: Cygnus Loop

ROSAT



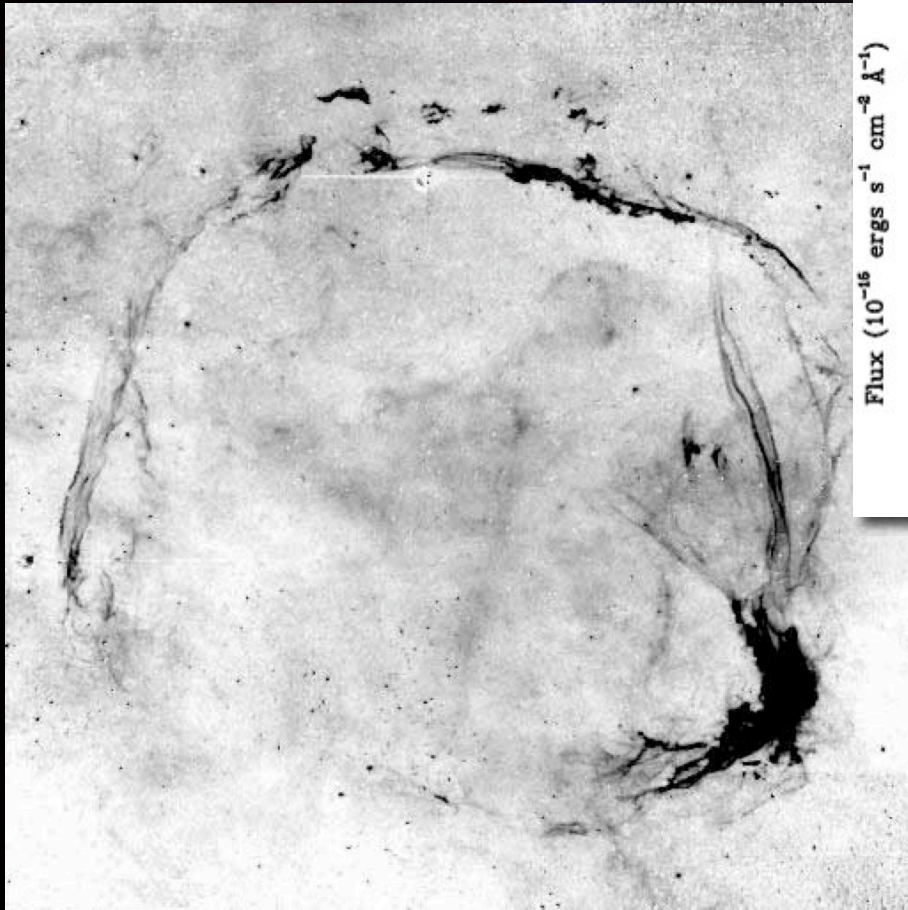
Mostly radiative $H\alpha$



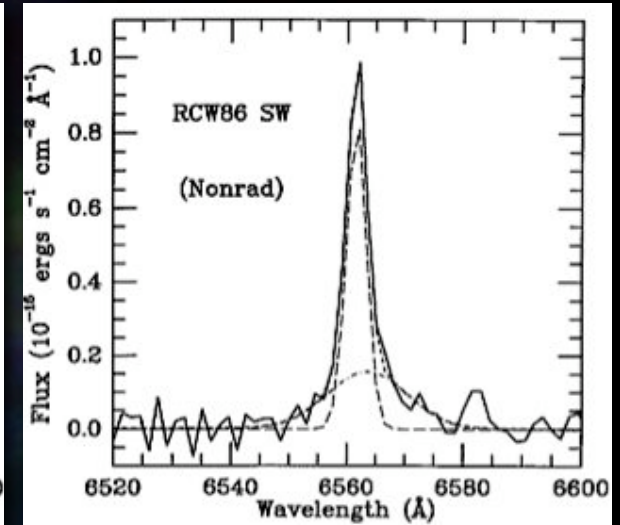
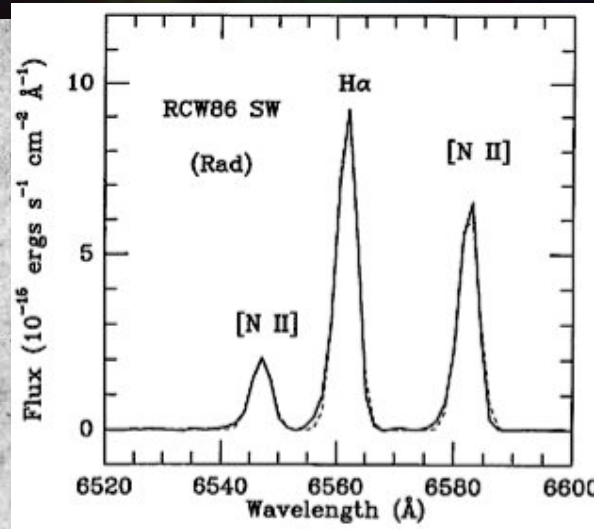
Non-radiative $H\alpha$ filament (Blair et al.)



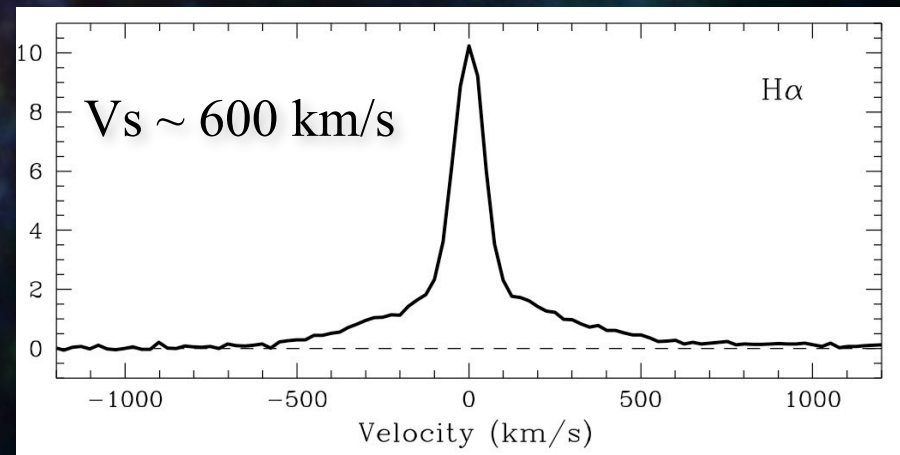
RCW 86 (SN 185?)



A combination of
radiative (bright) and
non-radiative shocks
(Smith 1997)



A radiative/non-radiative spectrum
(Long & Blair 1990)



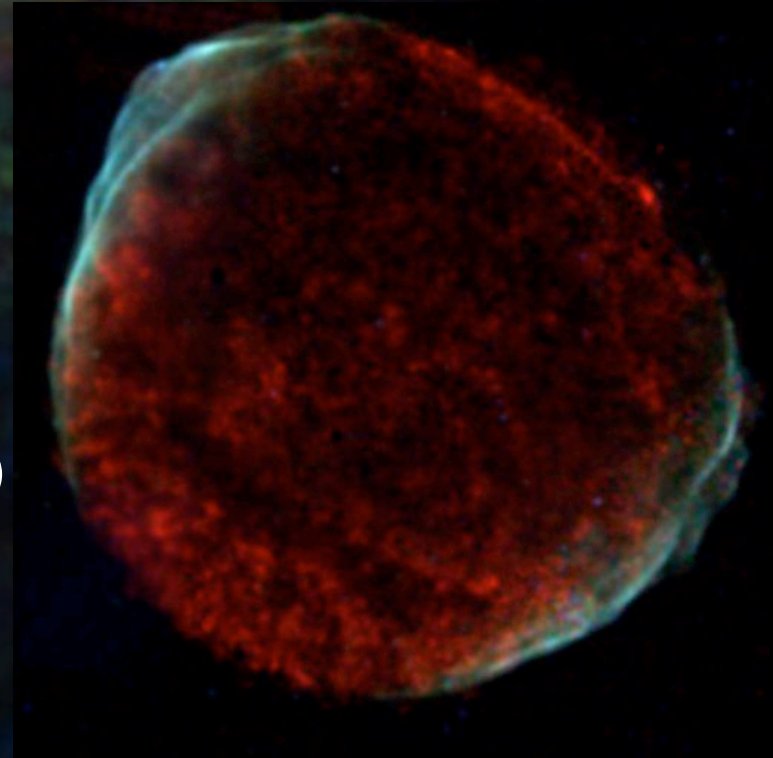
Non-radiative spectrum (Ghavamian et al. 2003)



Measuring Thermal Doppler Broadening: SN 1006

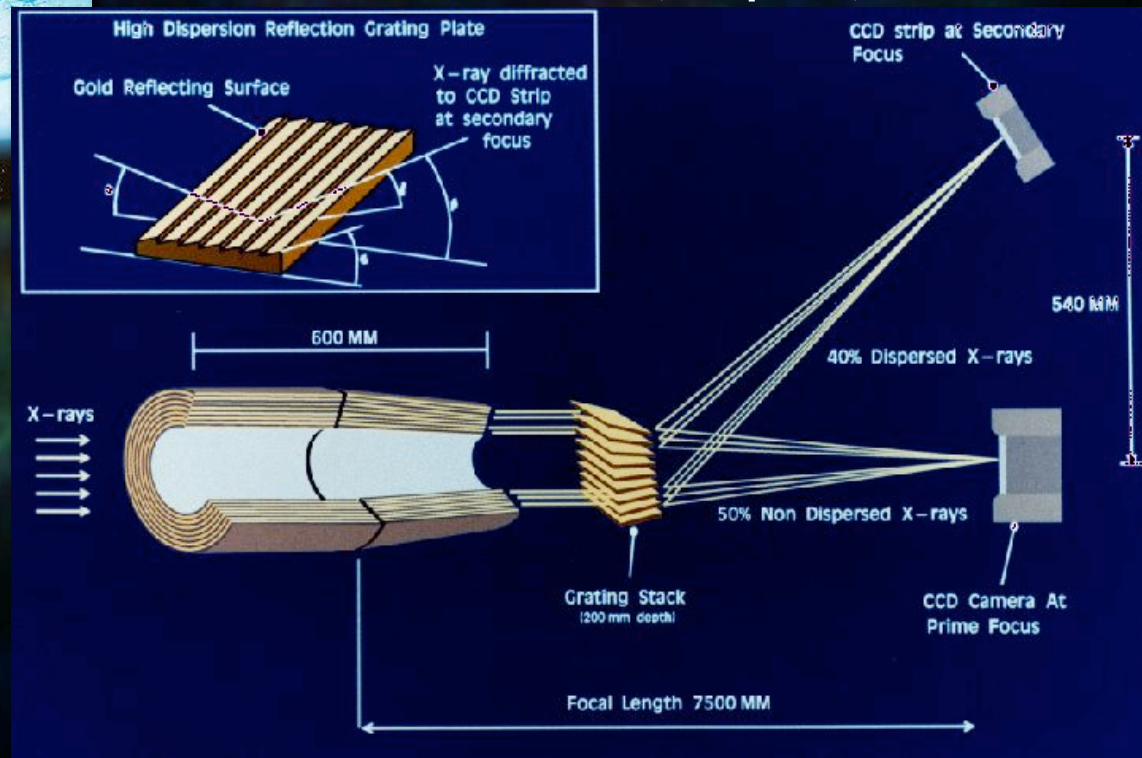
Why SN1006?

- Low density (0.1 cm^{-3}), young ($\sim 1000 \text{ yr}$)
→ low $n_e t$ ($\sim 3 \times 10^9 \text{ cm}^{-3} \text{ s}$)
- Likely to be far out of equilibrium
- Can't measure proton, use O VII instead
- Ion broadening more extreme for low $n_e t$
- Young SNR → Fast shock, more broadening
- Large SNR (30 arcmin), easier to isolate shock front

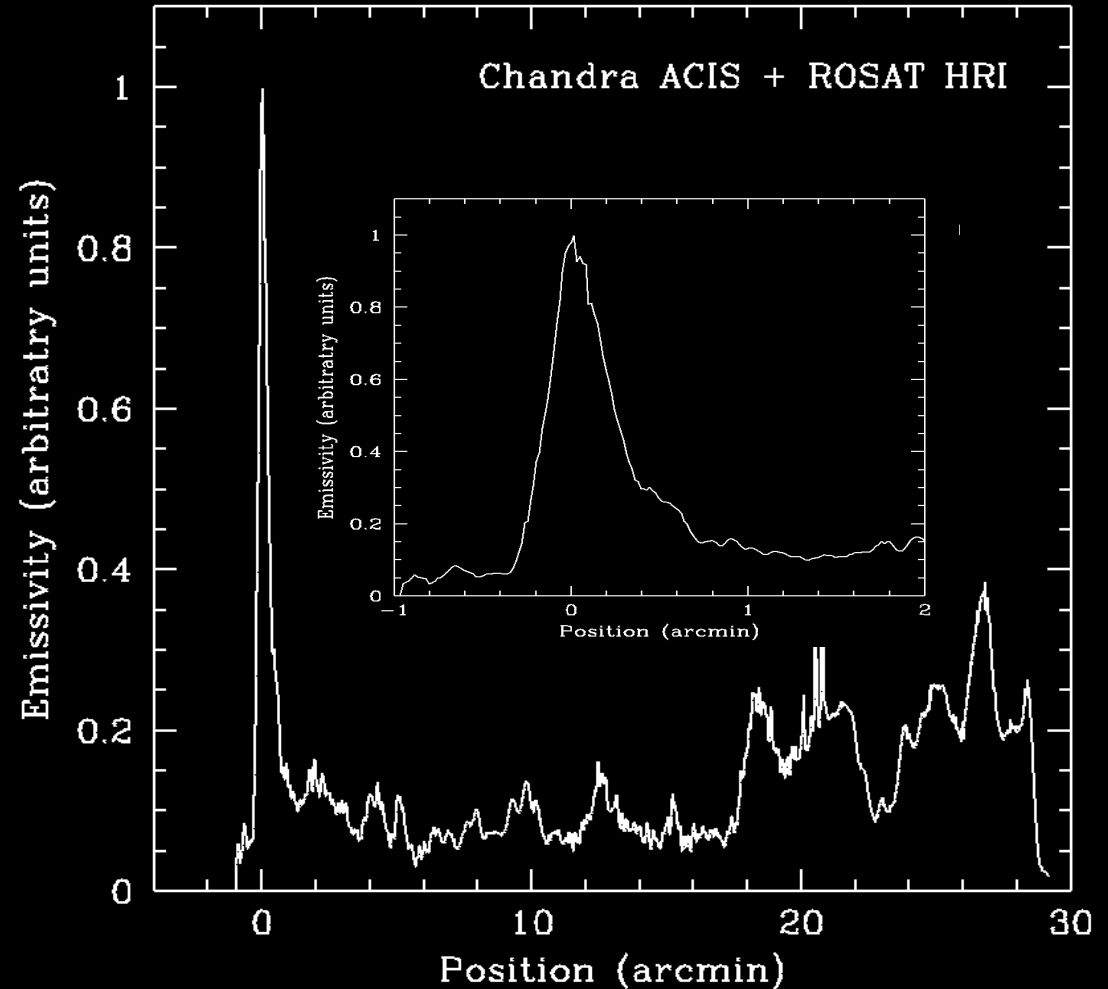
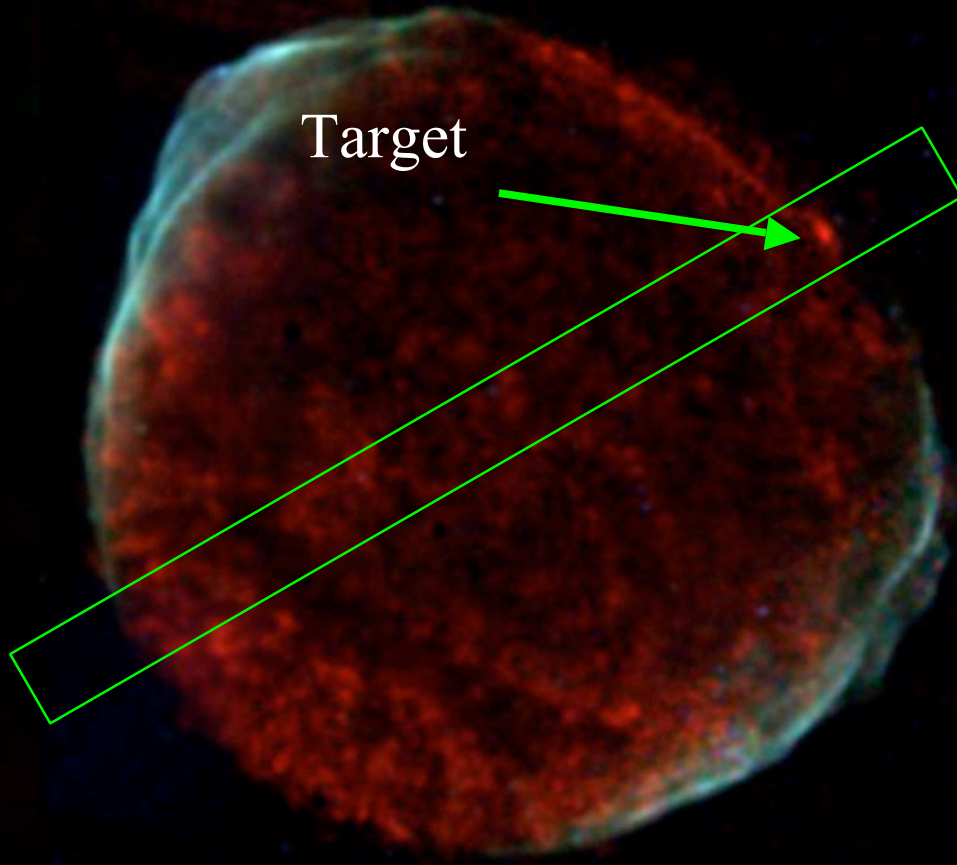


Observing SN1006 with XMM-Newton's Reflective Gratings

- Three telescopes
- Two reflective gratings
- No slit, spectral degradation:
$$\Delta\lambda = 0.124(\Delta\phi/1') \text{ \AA}$$



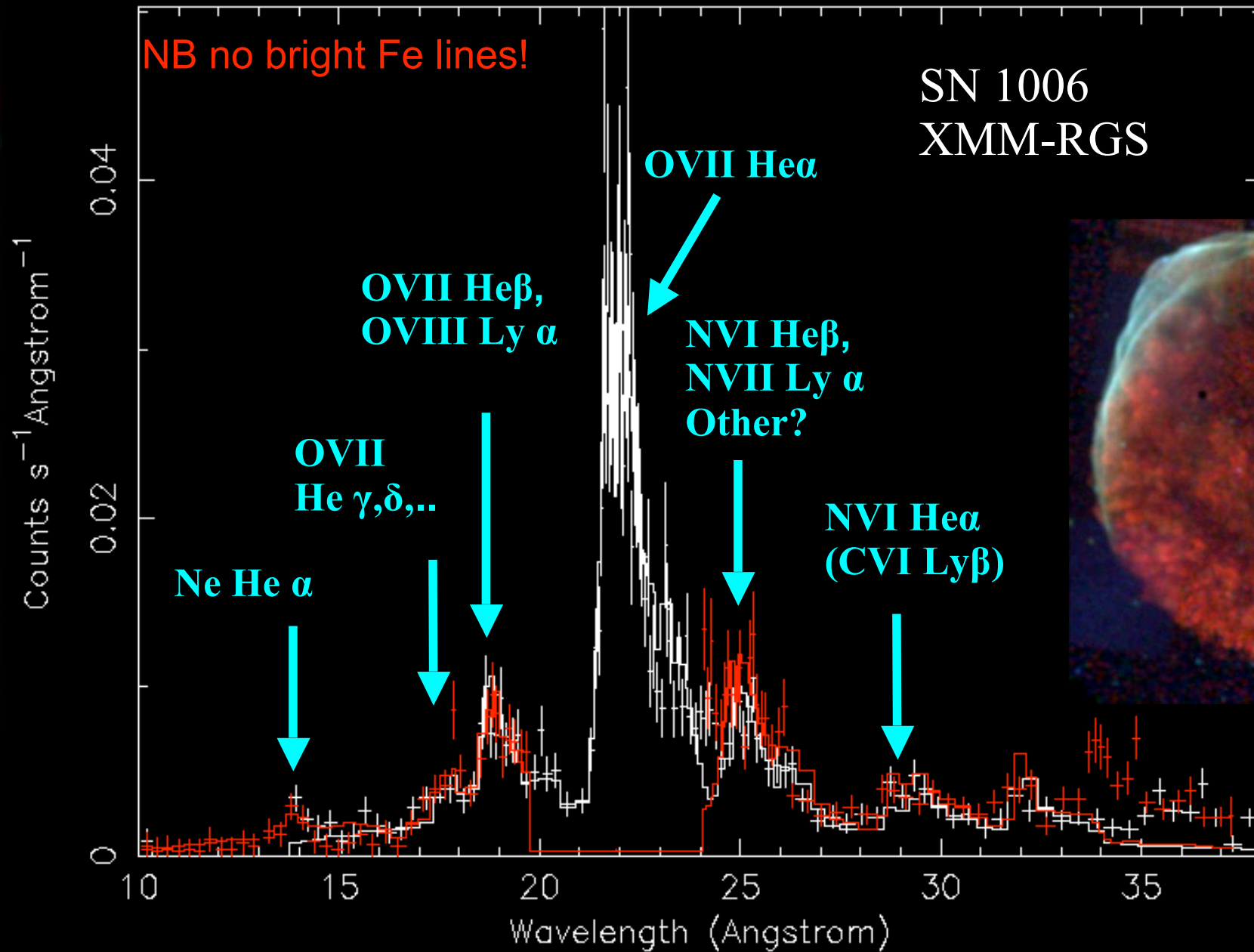
XMM-RGS High Resolution Spectroscopy



Knot size ~ 1 arcmin (0.4 arcmin FWHM)
Spectral resolution for bright lines
e.g OVII ($\sim 22\text{\AA}$): $\sim 1/170$



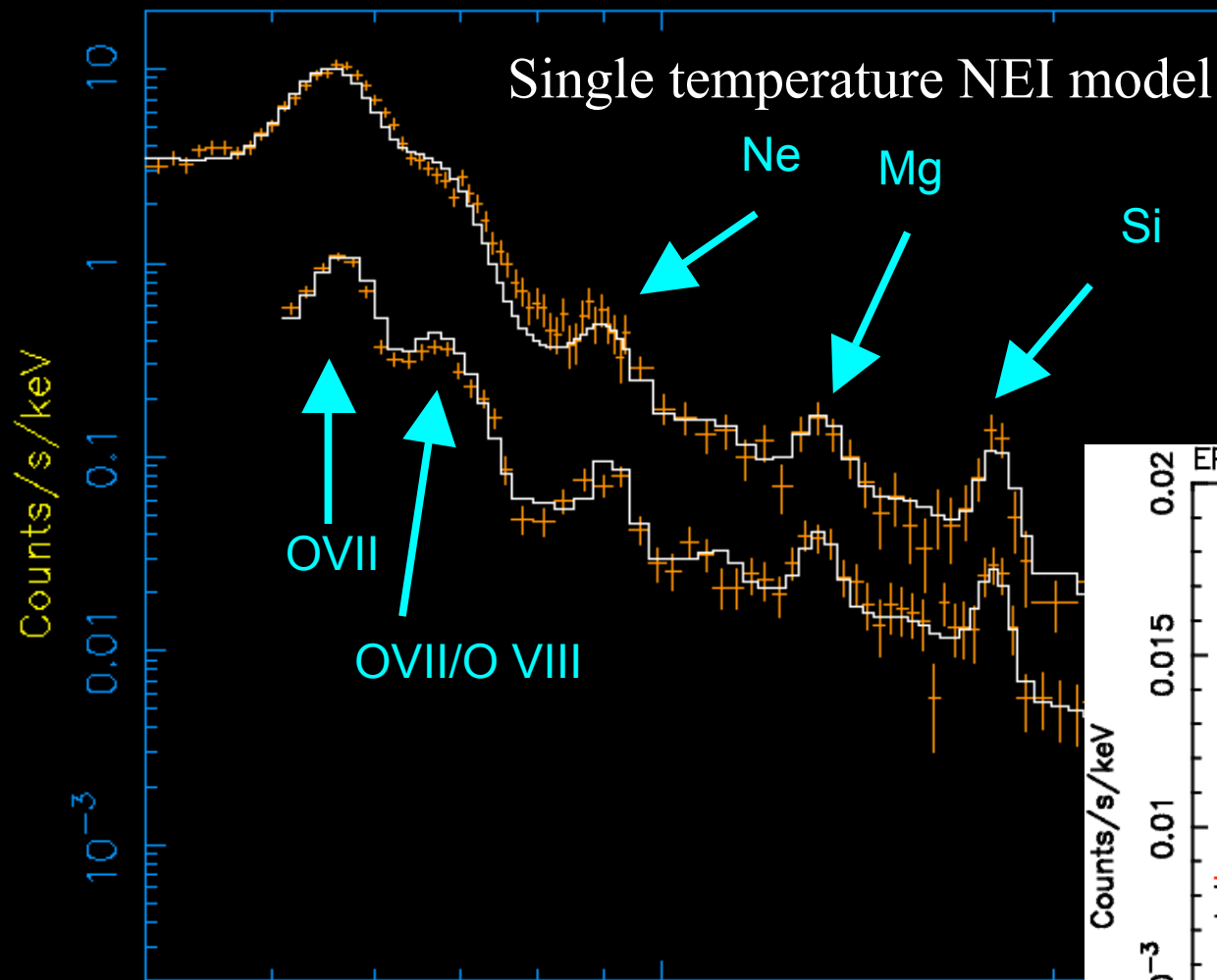
SN 1006 Slow temperature equilibration



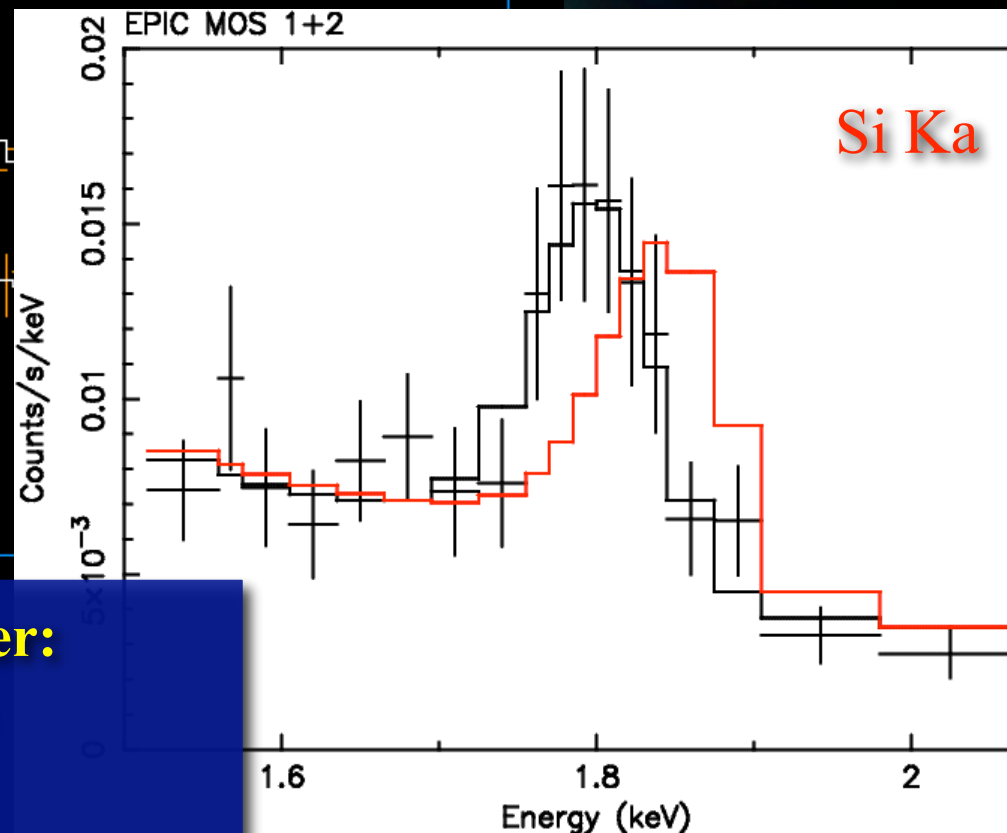
Vink et al. 2003



EPIC (CCD) spectra



- $n_e t = 2.4 \times 10^9 \text{ cm}^{-3} \text{ s}$
- $kT_e = 1.5 \pm 0.2 \text{ keV}$
- OVII dominated
- Si ab. $> 2 \times$ solar



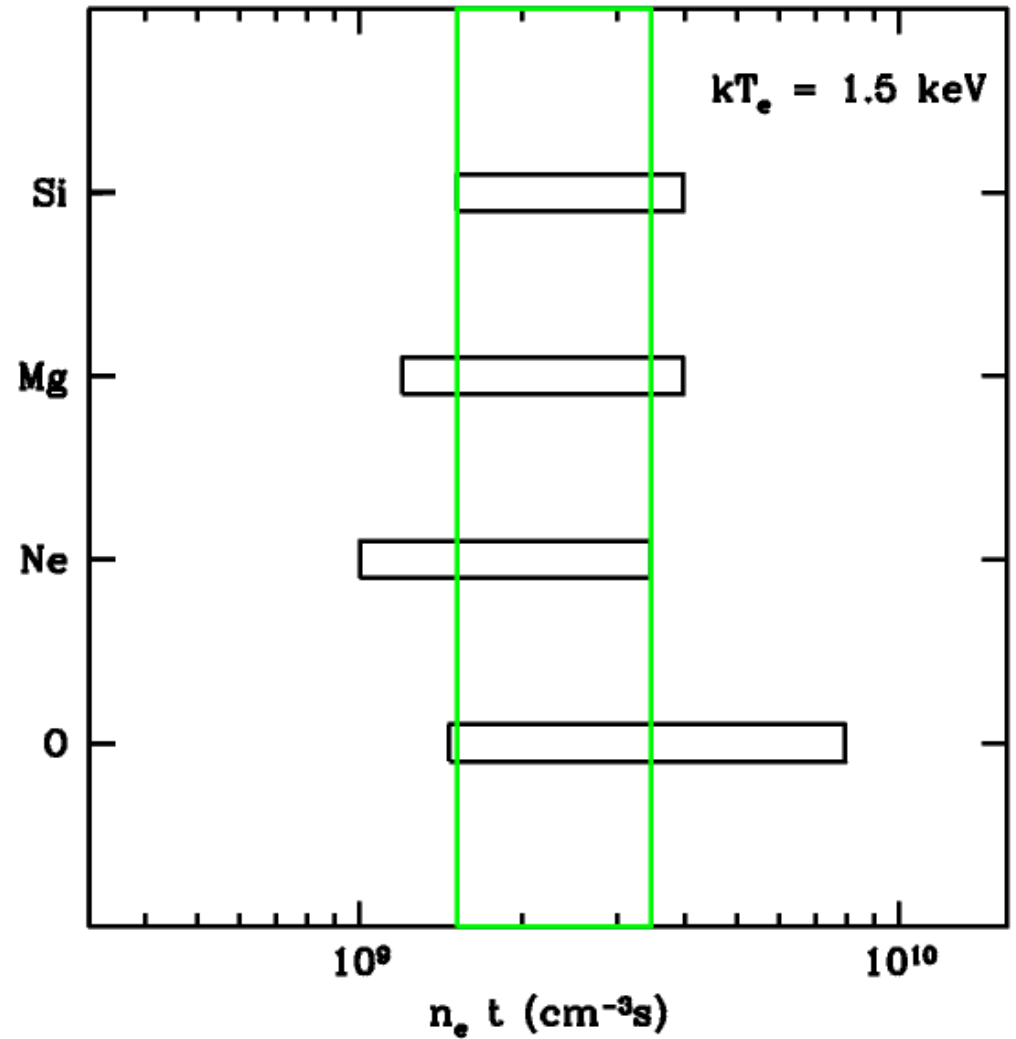
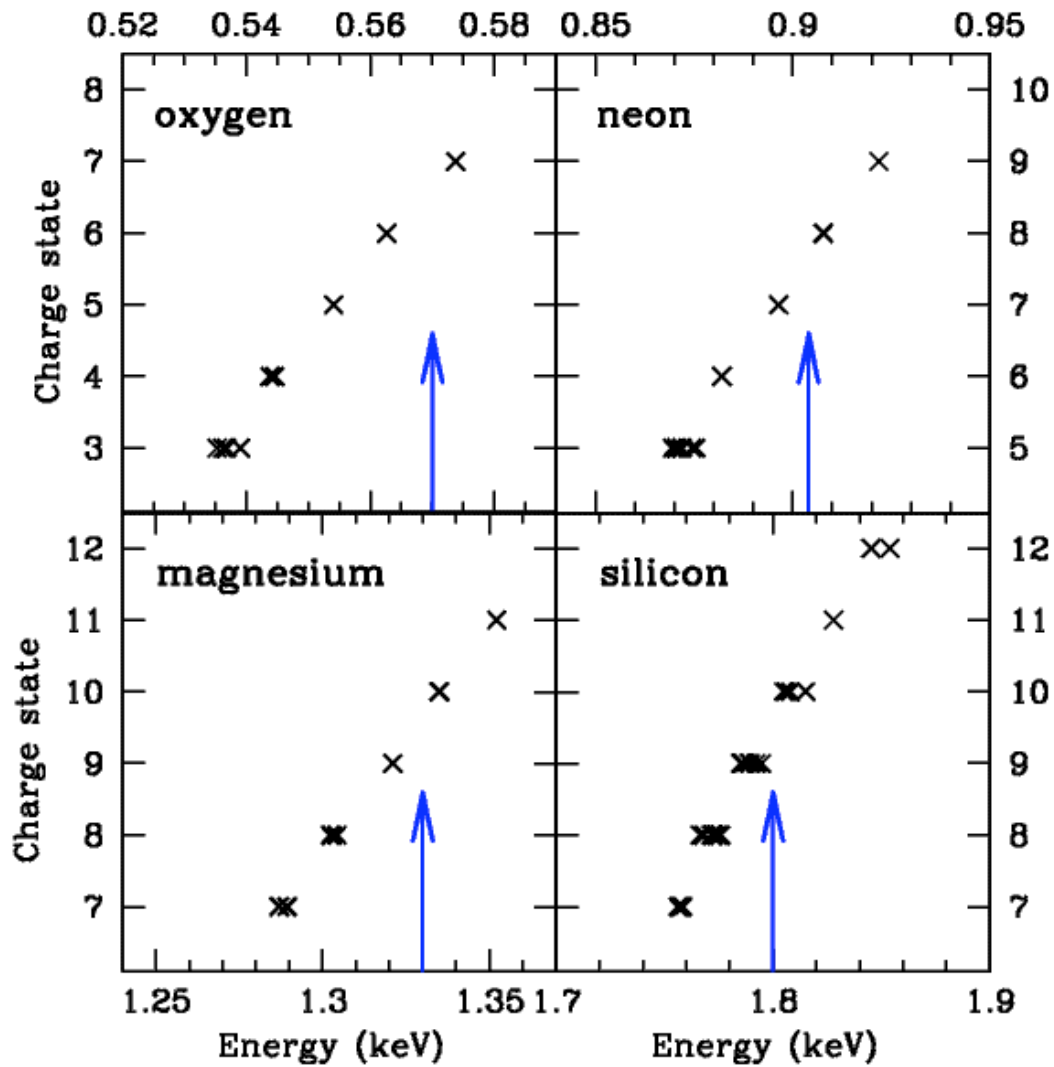
K α lines support low ionization parameter:

Mg $1.33 \pm 0.01 \text{ keV}$ (cf. 1.35 keV MgXI)

Si $1.80 \pm 0.01 \text{ keV}$ (vs 1.85 keV Si XIV)

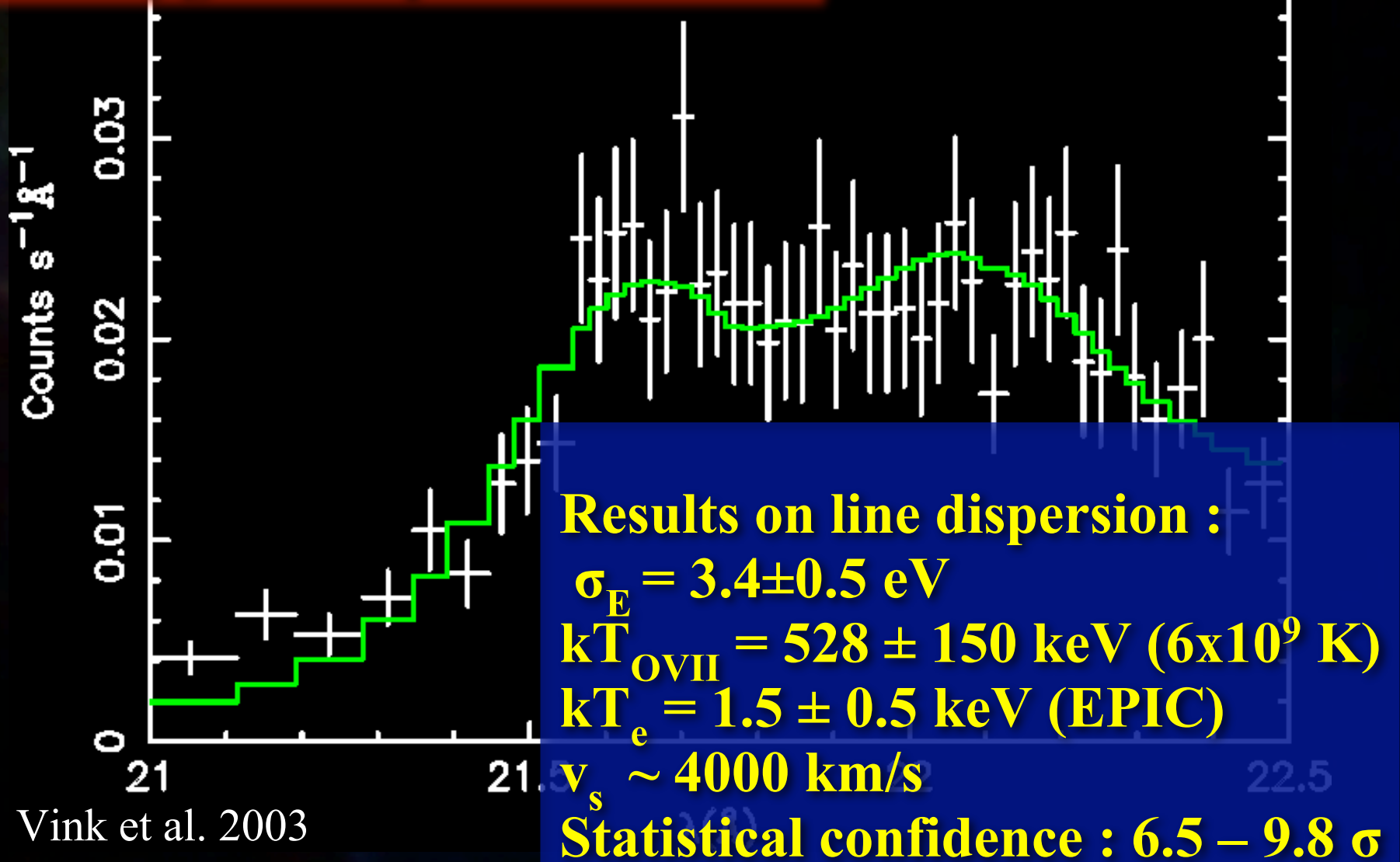


Constraining NEI



SN 1006 Slow temperature equilibration

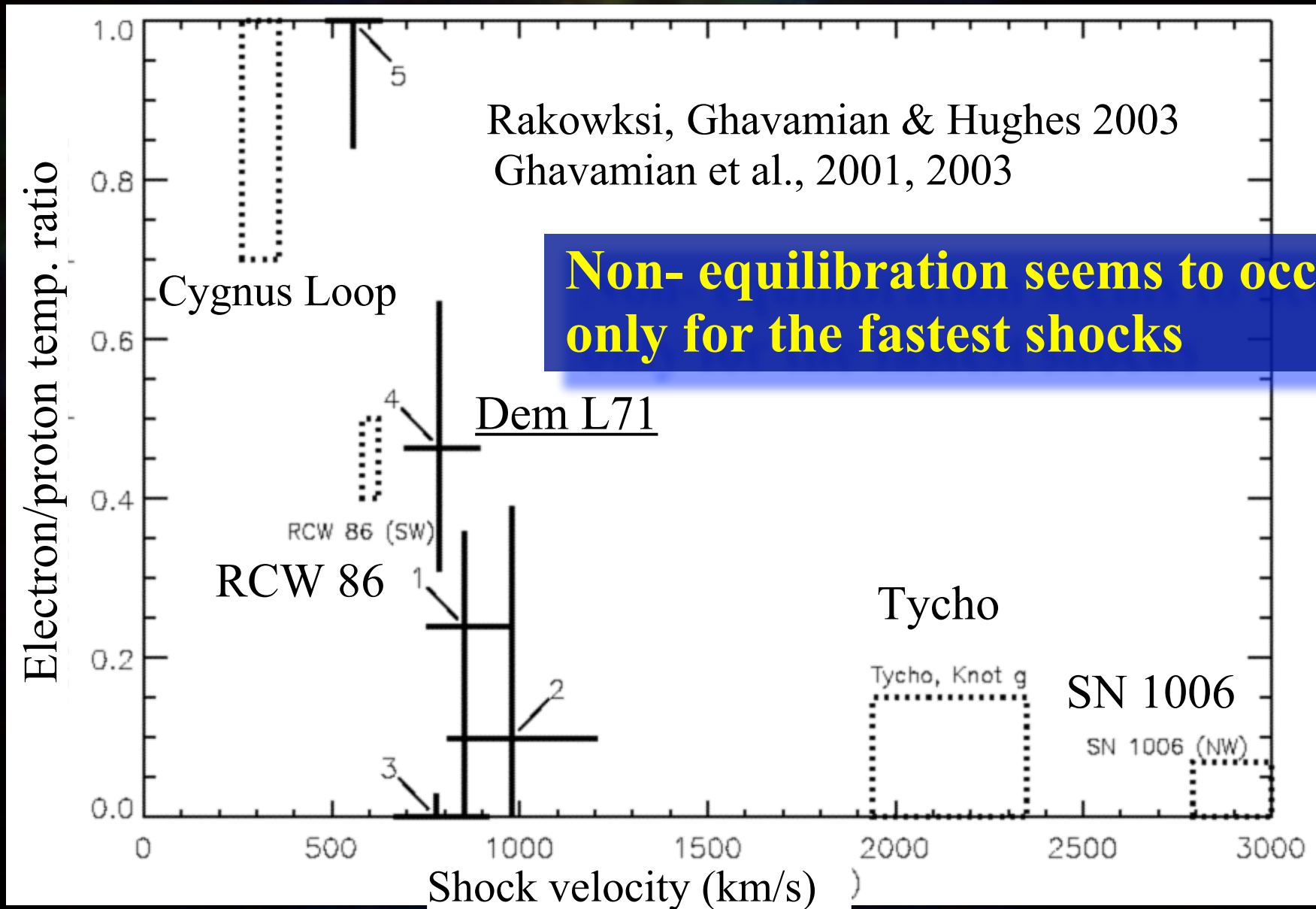
No rapid equilibration of electron and oxygen temperature!!



Vink et al. 2003



Equilibration versus Shock Velocity



The End of Lecture 1

